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Report 2550

ASPECTS OF PERFORMANCE EVALUATION OF WATERJET PROPULSION SYSTEMS AND A CRITICAL REVIEW OF THE STATE-OF-THE-ART

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Washington, D.C. 20007

ASPECTS OF PERFORMANCE EVALUATION OF WATERJET PROPULSION SYSTEMS AND A CRITICAL REVIEW OF THE STATE-OF-THE-ART

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HYDROMECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

October 1967

Report 2550

ASPECTS OF PERFORMANCE EVALUATION OF WATERJET PROPULSION SYSTEMS AND A CRITICAL REVIEW OF THE STATE-OF-THE-ART

by

John H. Brandau

ABSTRACT

Characteristics peculiar to waterjets may make this type propulsion capable of overcoming some of the problems facing high-speed marine propulsion. As a basis for judging the potential of waterjets in relation to other propulsion methods, a study was conducted to determine the state-of-the-art of waterjet technology. Available literature was surveyed with emphasis on: (1) performance criteria and performance data, and (2) performance evaluation and experimental techniques. A review of the existing work indicates a general lack of definitive experimental data. Although the greatest apparent need is for experimental information on the design of efficient and cavitation-free high-speed inlets, work is also needed on light-weight pumps which are capable of sustained high performance under relatively severe conditions. It was also found in the literature that thrust efficiency was usually confused with propulsive efficiency. Propulsive efficiency is equivalent to the product of thrust efficiency and the hull/waterjet interaction efficiency. Therefore, propulsive efficiency is a more definitive performance parameter but is inherently more difficult to obtain. The requirement of separating resistance and propulsive forces in determining this efficiency leads to model experiments. A review of model experimental techniques and facilities shows the capability for carrying out the necessary experiments.

ADMINISTRATIVE INFORMATION

This literature survey was conducted as part of the In-House Developmental Program of the Naval Ship Research and Development Center and funded under Subproject S-F013 01 03, Task 11274. The material is very similar to that in Paper 60-360 of the Advance Marine Vehicles Meeting jointly sponsored by the American Institute of Aeronautics and Astronautics and the Society of Naval Architects and Marine Engineers at Norfolk, Virginia, May 22-24, 1967.

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NOTATION

Symbol	Quantity	Mass Length Time Dimensions
C_p	$\frac{p - p_o}{\frac{1}{2}\rho V^2}$	
d	Diameter	L
e	Mean roughness height	L
E	Euler number $\left(V/\sqrt{\frac{\rho}{2\Delta p}}\right)$	
F_n	Froude number $(V/\sqrt{\ell g})$	
g	Gravitational acceleration (ft/sec^2)	L/T^2
H	Pump head rise (ft)	L
H_e	Exit nozzle head (ft)	L
H_i	Inlet head (ft)	L
H_1	Absolute pressure head at shaft	L
H_L	Head loss of system (ft)	L
H_{sv}	Net positive suction head (npsh) (ft)	L
H_s	Static head (ft)	L
J	Advance ratio (V/nd)	
K_H	Head rise coefficient (gH/N^2d^2)	
K_L	System loss coefficient $(H_L/V^2/2g)$	
K_q	Torque coefficient (q/N^2d^5)	
K_T	Thrust coefficient (T/N^2d^4)	
k	Jet velocity ratio (V_j/V)	
ℓ	Length (ft)	L
M	Mach number $\left(\sqrt{\rho V^2/E}\right)$	

Symbol	Quantity	Mass Length Time Dimensions
N	Rpm or rps (rev/sec)	$1/T$
N_S	Pump specific speed $(NQ^{1/2}/(gH)^{3/4})$	
N_{VA}	Jet loss energy (ft-lb)	ML^2/T^2
N_{VK}	Additional loss energy (ft-lb)	ML^2/T^2
N_{VT}	Propulsion loss energy (ft-lb)	ML^2/T^2
N_T	Thrust-horsepower energy (ft-lb)	ML^2/T^2
O.P.C.	Propulsive coefficient (P_E/P_B)	
p	Pressure, (local), (lb/ft^2)	M/LT^2
P_E	Effective horsepower (RV/550) (ft-lb/sec)	ML^2/T^3
P_B	Brake horsepower $(2\pi Nq_{brake}/550)$ (ft-lb/sec)	ML^2/T^3
P_D	Propeller horsepower (delivered)	ML^2/T^3
P_I	Power input (ft-lb/sec)	ML^2/T^3
P_O	Power output (ft-lb/sec)	ML^2/T^3
P_P	Pump horsepower $(\rho gH/550)$ (ft-lb/sec)	ML^2/T^3
P_S	Shaft horsepower (ft-lb/sec)	ML^2/T^3
P_T	Thrust horsepower (TV/550) (ft-lb/sec)	ML^2/T^3
p_v	Vapor pressure (lb/ft^2)	M/LT^2
p_o	Free-stream static pressure (lb/ft^2)	M/LT^2
Q	Volume flow rate (ft^3/sec)	L^3/T
q	Shaft torque (lb-ft)	ML^2/T^2
R	Resistance (lb)	ML/T^2
R_e	Reynolds number $(V\ell/\nu)$	
r	Impeller radius (ft)	L

Symbol	Quantity	Mass Length Time Dimensions
T	Thrust (lb)	ML/T^2
$1-t$	Thrust deduction (1-R/T)	
u_a	Axial velocity (ft/sec)	L/T
u_t	Tangential velocity (ft/sec)	L/T
V	Ship velocity (ft/sec)	L/T
V_a	Propeller advance velocity (ft/sec)	L/T
V_i	Inlet velocity (ft/sec)	L/T
V_j	Jet velocity (ft/sec)	L/T
V_p	Velocity through pump (ft/sec)	L/T
V_o	Free stream velocity (ft/sec)	L/T
W	Weber number $(\rho \ell V^2/\xi)$	
w	Wake fraction $(1 - V_a/V)$	
w_1	Weight rate of flow (lb/sec)	ML/T^3
β	Advance angle (deg)	
β_i	Hydrodynamic pitch angle (deg)	
ΔH	$(H_e - H_i)$ (ft)	L
ΔV	$(V_j - V_i)$ (ft/sec)	L/T
η_A	External efficiency	
η_D	Propulsive efficiency (P_E/P_D)	
η_{hull}	Hull efficiency (1-t/1-w)	
η_{id}	Jet efficiency	
η_I	Ideal jet efficiency	
η_{jpr}	Real jet propulsive efficiency	
η_p	Propeller efficiency $\left(\dfrac{T\ V_a/550}{P_D}\right)$	

Symbol	Quantity	Mass Length Time Dimensions
η_{pump}	Pump efficiency	
η_s	System efficiency	
η_{tr}	Internal efficiency	
γ	Specific weight (lb/ft^3)	M/L^2T^2
λ	Linear ratio (ℓ_s/ℓ_m)	
μ	Coefficient, dynamic viscosity ($lb\text{-}sec/ft^2$)	M/LT
ν	Coefficient, kinematic viscosity (ft^2/sec)	L^2/T
ω	Angular velocity (radian/sec)	$1/T$
ϕ	Flow coefficient (Q/Nd^3)	
ρ	Mass density ($slugs/ft^3$)	M/L^3
σ	Cavitation index ($H_1/V^2/2g$)	
σ_{Thoma}	Thoma cavitation number (H_{sv}/H)	
τ_o	Shear stress (lb/ft^2)	M/LT^2
ξ	Surface tension (lb/ft)	M/T^2

FOREWORD

This survey has been prepared in an effort to clarify the present state of knowledge regarding the hydrodynamics of waterjet propulsion. It is hoped that this report will enable the reader to acquaint himself with the basic problems involved, the work that has been done up to the present time, its relative significance, and the areas in which further research appears to be needed.

INTRODUCTION

An increase of interest in waterjet propulsion of marine craft has been noted in the past few years. This type of propulsion is not new since, as pointed out by Taggart,[1] evidence exists of experimental evaluation of a jet-propelled craft in England as far back as 1661. Taggart states that, by 1900, certain inherent disadvantages of hydraulic jet propulsion regarding ducting losses and weight were recognized. Moreover, performance improvements within the succeeding 60 years have not been impressive, and the attractive advantages of waterjets may not have yet been fully realized. Extensive historical surveys have also been made by Papir[2] and Schuster et al.[3] Another brief history of waterjets[4] was published in 1962 by Engel et al., in a paper "Axial Flow Pumps for Waterjet Propulsion."

By waterjet is meant a marine propulsor in which water is fed to internal pumps which add energy and expel the water aft through a nozzle. The water is exhausted at a higher velocity than that of the incoming stream and thrust is achieved through the resulting momentum exchange. It can also be classed as an internal ducted propeller for which the duct is long. The waterjet system, by definition in this study, is that system using water alone as the working media, as opposed to those using water-gas mixtures.

A waterjet propulsion system, in distinction from all other types of shipboard jet propulsion systems, is located mostly within the hull of the ship. Therefore it must, of necessity, have three basic elements:

1. an intake duct which inducts fluid from outside the ship's hull,

2. a pump for transmitting energy to this fluid, and

3. an exhaust duct and nozzle which guide the jet of fluid back out of the hull.

It could be expected that a waterjet-propelled ship, having no

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[1]References are listed on page 63.

elements protruding beyond the limits of the ship's hull lines, would have less drag (other things being equal) than a hull fitted with a conventional propeller. On the other hand, however, the flow of fluid through the internal waterjet system is accompanied by additional hydraulic losses. The resistance may change significantly when the hull is propelled since operation of the propulsion system changes the distribution of pressures on the hull. Ingestion of boundary layer flow in conjunction with lower jet velocity and higher mass flow rate can lead to increased ideal efficiency. On the other hand, a force reacting opposite to the intake induction momentum can suck the hull down with possible increase in trim and thus form drag. Also, ejection of the jet in the vicinity of the ship's wake can change the magnitude of the useful thrust. These examples are given as possible interaction effects of hull flow on waterjet flow and vice versa. Determination of the reaction coefficients for such a problem with experimental verification is a prime need in waterjet propulsion research.

Application of a waterjet system can be considered successful if it allows satisfactory operation of the craft and accomplishes this through alleviation of some of the significant limitations of other propulsors for that particular application. It is interesting to formulate an initial philosophy about waterjet propulsion before studying it in detail. First of all, unless a ship designer runs into serious problems in attempting to utilize conventional or fully cavitating propellers, he probably would not consider waterjets because the overall propulsive efficiency of the waterjet is always degraded to an extent by the induction and ducting losses not inherent with propellers. Too, the design of the hull in which a waterjet will be fitted should be considered a fundamental part of the propulsion system consideration if anywhere near optimal craft operating performance is desired.

The importance of waterjets for marine propulsion can be ascertained by consideration of what this form of propulsion has to offer to the ship designer. It is found to be generally more expensive, less efficient, heavier, and the propulsor itself is more complicated than a conventional propeller. However, for certain special purposes such as shallow-draft operation or high-power, high-speed operation, waterjet propulsion may permit the elimination of, or may diminish, unavoidable disadvantages

inherent with the use of a propeller. (Detailed advantages and disadvantages of waterjets will be enumerated in the section on General Considerations.)

Although waterjet propulsion systems may offer attractive features which would be highly desirable for certain marine applications, a number of significant development problems have to be solved before the full use of such propulsors can be realized. These problem areas will be discussed in detail later on in the report, but to mention a few, they include: (1) proper design of hull inlet to prevent separation and cavitation, especially during operations in a seaway; (2) optimization of system ducting and pump location to minimize friction losses and pump elevation losses; (3) design of high-speed axial-flow waterjet pumps capable of meeting cavitation, efficiency, and off-design performance required for vehicle takeoff and cruise conditions; and (4) adequate methods and techniques for model-scale performance evaluation and prototype system performance evaluation.

In view of these and other formidable hydrodynamic problems, the Naval Ship Research and Development Center is establishing a research and development program for this form of ship propulsion. The program will be aimed at defining and solving the hydrodynamic problems existing in the achievement of high performance of waterjet-propelled craft. Concentration will be on those areas for which the state-of-the-art survey presented in this report indicates the greatest lack of technical information.

This report presents a critical survey of the technical literature currently available on waterjet propulsion of marine craft. Emphasis is placed on the real problems which exist today in this area. First, a discussion of naval applications for waterjet propulsion in light of the advantages and disadvantages of this type of propulsion is given. Second, theoretical treatments and experimental performance techniques for evaluating system components and complete installed systems, are discussed. Discussion of performance evaluation information found in the literature is included here. The literature pertaining to general waterjet propulsion considerations is treated next. This is followed by a list of unsolved problems existing in light of the conclusions reached by theory and experiment. A recommendation for performance parameters and modeling techniques

is included.

Based on this information, conclusions will be drawn regarding what are felt to be the knowns and unknowns (problems) in the state of the art. A recommended research and development program for solving the apparent problems will be presented. An annotated bibliography and appendices containing pertinent background material will complete the report.

GENERAL CONSIDERATIONS

CONSIDERATION OF EXISTING WATERJET LITERATURE

A major portion of this study involves a consideration of the available literature regarding hydrodynamic performance evaluation of waterjet propulsion systems. The main purpose of the study was the determination of and suggestions for finding solutions to the problems facing the task of acquiring efficient reliable waterjet propulsion systems for special types of marine craft.

The papers and reports surveyed for this study are varied in their treatment of aspects of waterjet propulsion. Some are feasibility studies, some are general studies proposing procedures for waterjet propulsion system design, and others fall into the category of theoretical and/or experimental investigations. The experimental work lends itself somewhat to a tabulation of variables considered and measurements made (see Table 2 in Appendix). The information obtained from the literature pertains to the theoretical and experimental treatments of:

1. waterjet propulsion system components, including pumps, inlets, and ducting;

2. complete waterjet propulsion systems;

3. waterjet propulsion system installation in a hull including efficiency, model and prototype testing.

As far as those papers dealing with theoretical approaches or in feasibility studies, an attempt has been made to briefly present their significant points in the text of the survey chapter. An annotated

bibliography is included to concisely provide some insight to the reader on the surveyed material considered to lie within the scope of this study.

APPLICATIONS

(Emphasis of Important Differences between Waterjet Application to: Planing Boats, Hydrofoil Craft, and Captured Air Bubble (CAB) Craft)

Current U. S. waterjet propulsion applications include small pleasure planing craft, small military river patrol boats,[5] and hydrofoil craft. Serious proposed applications include larger military patrol planing boats, high-speed hydrofoil and captured air-bubble craft.

The bulk of the small pleasure boats are of the 200 to 300 horsepower range. Several thousand are now in service, with propulsors of the Buehler,[6] Berkeley, or Jacuzzi design, for the most part. European manufacturers have comparable units available. Some idea of the qualitative operational performance of complete waterjet-propelled hulls can be obtained, taking into consideration the mission of the craft, by studying reports of owners and operators. Efficiency is not a prime requirement for private water ski or sport runabouts of the present waterjet era, and manufacturers rarely take pains to determine real efficiency. Instead, characteristics such as speed, maneuverability, boat handling, noise and vibration, and desire to eliminate the external propeller for safety's sake are stressed.

At the present time some of the in-service designs are good as far as ahead maneuvering and handling, but efficiency is lower than comparable conventional propulsion installations.

Most of the military river patrol boats now in service in South Vietnam are in the 30- to 50-foot length range. Upwards of 150, 30-foot, 25-knot Bellingham Boat Works hulls fitted with twin Jacuzzi 225-hp waterjets have been sent to U. S. forces in Southeast Asia. The mission there involves patrol of shallow, weed-infested rivers and streams with a small crew to operate the boat and man a deck-mounted gun. Reports of operational problems of weed-choking and backing maneuvering have been received.

Recent attention has been given to the use of waterjets for high-speed oceangoing ships[7,8] of the nondisplacement type. At present, serious consideration in this area is mainly limited to hydrofoil craft and, more recently, air-cushion vehicles including the captured air bubble (CAB) type. Certain major design tradeoffs for these ships are highly dependent on mission cruising range. For the smaller high-speed but short-range (cruise range duration of a few hours) craft, it is essential that the weight of propulsion machinery be kept low; however, high-system efficiency may not be a critical requirement. High-system efficiency becomes increasingly important as the ratio of fuel weight to gross weight increases and, in the case of a long cruise range oceangoing craft, fuel weight is significant. At the present time, consideration is being given to the use of CABS, displacing several thousand tons, for long-range oceangoing service with hydrofoil craft, limited to short-range missions. In this respect, the CAB sidewall configuration is encouraging with respect to achieving a more efficient water ducting system than can be realized with a hydrofoil craft, up-the-strut configuration.

The following table indicates the major powering requirements of the aforementioned craft:

Speed (knots)	Craft	HP Rating
25-30	Planing-type Pleasure Boats	225-450
30	31-ft River Patrol Boat	450
55	50-ft Planing Patrol Boat	3500
50	70-ton Hydrofoil (PGH)	3700
50	110-ton Hydrofoil (PCH)	6200
65	500-ton CAB	25,000
85-100	4000-ton CAB	200,000

APPARENT ADVANTAGES AND DISADVANTAGES

The selection of any propulsion system is based on a value judgment of the advantages and disadvantages of that system. Following is a list of advantages and disadvantages inherent in waterjets; however, the final application will determine how these are weighed and compared with other systems.

Although practically every publication found in the literature of waterjet propulsion mentions certain advantages inherent in waterjets over other forms of propulsion, very few unqualified statements can actually be made in this regard. This is due to the fact that a possible advantage of a waterjet is dependent on the particular application and also must be compared with all other existing propulsor types. Advantages of waterjet are:

1. With a waterjet, it is possible to eliminate external underwater appendages.

2. A freer choice of location of the propulsion machinery than is normally found.

3. Elimination of complex transmission machinery where right-angle drives are required, such as in hydrofoil craft strut propeller applications.

4. Possible alleviation of underwater radiated propeller cavitation noise through more control over cavitation and removal of the propeller from the main body of water.

5. Steering and maneuvering control directly from the propulsor (note, however, that this is done by attaching control surfaces to the waterjet nozzle which is effectively calling the rudder part of the propulsor). It should be noted that right-angle drive units have been successfully built for 360-deg directional control.

6. Detrimental effects of propeller vibration may possibly be alleviated due to control of the impeller inflow characteristics over that of an open propeller.

7. For towing boats and for icebreakers, the waterjet can produce greater tow-rope pulls than an open propeller; however, a Kort nozzle,

in this regard, will be more efficient.

Most statements regarding disadvantages must also be qualified in light of application and competitive propulsors. However, it can be stated that:

1. Waterjet systems have higher weight than most other practical propulsor systems. Note that the weight of the water in the propulsion system must be included in the system weight.

2. In general, a waterjet system will not be as efficient as a propeller system; i.e., more horsepower will be required to perform a particular function with a waterjet system.

3. The possibility of cavitation at the waterjet inlet and other places in the inlet system, which can adversely affect performance, means that there are several sources of cavitation to be considered.

4. Impeller access compared with conventional propeller designs is poor, making inspection, repair, or removal of debris difficult.

SYSTEM COMPONENT PERFORMANCE

EFFICIENCY

The overall propulsion performance of special-mission, high-speed craft is dependent on a number of significant factors. For a specific mission, at a specified design speed, consideration should be given to: payload, horsepower, specific fuel consumption (SFC), range, dash capability, and gross weight, among other factors.

A number of special performance coefficients or merit factors have been proposed to lump together these variables into a meaningful parameter. Examples are the so-called Karman-Gabrielli factor and Telfer's merit factor.[10] The Karman-Gabrielli factor is one which is based on the Karman-Gabrielli line[9] which is an empirical representation of power-speed relationships of various vehicles.

$$MKG_1 = \frac{1}{8800} \left(\text{equivalent } \frac{L}{D} \text{ ratio}\right) \frac{W_{payload}}{W_{initial}} V \qquad [1]$$

where $\frac{L}{D}$ =lift-drag ratio.

It is evident that a portion of such merit factors represents the hydrodynamic propulsion parameters.

The following discussion pertains to the choice of a meaningful or definitive hydrodynamic propulsion parameter. On normal conventional propeller-hull installations, overall powering performance of the craft is based on:[10,11]

$$\text{O.P.C.} = \frac{\text{effective horsepower}}{\text{brake horsepower}} = \frac{P_E}{P_B} = \frac{RV}{P_B} = \frac{T(1-t)V}{P_B} = \eta_p \times \eta_{hull} \qquad [2]$$

where P_B = brake horsepower measured at the output of the prime mover,

R = towed hull drag (sometimes utilizing bare hull drag and at other times using appended hull drag),

T = required thrust,

t = thrust deduction, and

η_p = propeller efficiency in the "behind ship" condition.

Reference 10 by Rossell and Chapman and Reference 11 by H.E. Saunders point out in detail the terminology and usage of O.P.C. and propulsive efficiency (quasi-P.C.) in conventional marine propulsion applications.

For purposes of discussion of the efficiency of propulsion in this report, the term overall propulsive coefficient (O.P.C.) will not be used. Instead, the quasi-propulsive coefficient, sometimes called propulsive efficiency η_D will be used.

$$\eta_D = \frac{P_E}{P_D} = (\text{O.P.C.})\,\frac{P_B}{P_D} \qquad [3]$$

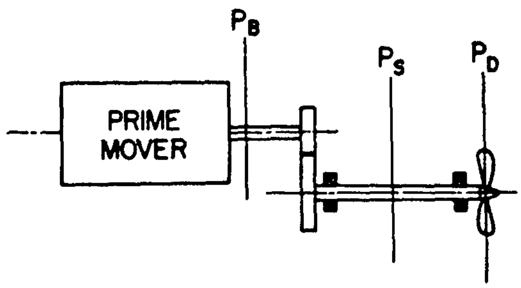
where P_E = effective power to overcome resistance,

P_B = brake power measured at output of prime mover, and

P_D = power delivered to propeller.

$\frac{P_D}{P_B}$ is termed transmission efficiency and reflects the power losses occurring between the prime mover coupling and the propeller due to shafting, bearings, etc.

It is more expedient to use P_D because model testing usually involves the measurement of P_D rather than P_B. On the other hand, in full-scale trial work, power P_S is normally measured by means of a torsionmeter on the inboard shafting, intermediate between the propeller and the prime mover. (See sketch below.)



SCHEMATIC OF POWER TRANSMISSION

The normal procedure at the Center is to measure P_D in model tests and correct this to predict the P_S of the full-scale ship. Because of the variation in possible locations for measuring P_S and since P_B would not correlate directly from model to full scale, it appears sensible to utilize P_D throughout this discussion.

Propulsive efficiency η_D is also, by definition,* equal to

$$\eta_D = \frac{RV}{P_D} \qquad [4]$$

where R = resistance in general.

A rather interesting situation exists here in that this definition of propulsive efficiency is not the definition of "propulsive efficiency" used by many workers in the field of waterjet propulsion. The expression most commonly found in the waterjet literature is equal to

* ITTC Standard Symbols, National Physical Lab., Ship Report 77 (Sep 1965)

$$\frac{TV}{P_S}$$

where P_S = shaft horsepower = P_D + shafting losses between the point of measurement and the impeller. This term can be referred to as thrust efficiency η_T since it is clearly not equal to the standardized propulsive efficiency. So

$$\eta_T = \frac{TV}{P_S} \qquad [5]$$

One reason that η_T has been widely used in waterjet analyses is that it is relatively easy to measure during sea trials and another is that it is of the form corresponding to the expression for Ideal Jet Efficiency η_I. η_I is sometimes also known as Ideal Propulsive Efficiency or Froude Efficiency.[12,13]

In attempting to improve the propulsive performance of a system, it is necessary to relate the overall propulsive efficiency of a waterjet-propelled craft to the aggregate of the propulsion component efficiencies. In conventional propulsion analyses

$$\eta_D = \frac{RV}{P_D} = \frac{T(1-t)V}{P_D} = \eta_{\text{propeller "behind"}} \times \eta_{\text{hull}} \qquad [6]$$

where R = barehull resistance (since this will be "base" drag)

$$\eta_{\text{propeller "behind"}} = \frac{TV(1-w)}{P_D}$$

$$\eta_{\text{hull}} = \frac{1-t}{1-w}$$

1-t = thrust deduction

The term (1-w), which is called wake gain, is not meaningful for waterjet

pumps because w, the wake fraction, is without specific meaning since the impeller is located in a long duct. Therefore, η_{hull} is not applicable to waterjet systems. Instead, for a waterjet, $\eta_{hull/inlet}$ must be defined.

A reasonable choice of form for relating the system component efficiencies to the overall propulsive efficiency is as follows.

Equating

$$\eta_D = \frac{RV}{P_D} = \frac{T(1-t)V}{P_D} \qquad \text{[6] repeated}$$

to

$$\eta_{pump} \times \eta_{jet} \times \eta_{system} \times \eta_{hull/inlet}$$

where $\eta_{pump} \times \eta_{jet}$ is essentially equal to $\eta_{propeller}$, depending on the way that the flow velocities are chosen;

η_{system} (η_S) by definition is proportional to the ratio of internal ingestion and ducting pressure losses to the free-stream dynamic pressure; and

$\eta_{hull/inlet}$ ($\eta_{h/i}$) which characterizes the effect on powering performance of the interaction of the inlet and hull, and which herein will be defined as (1-t) where $(1-t) = \frac{R}{T}$, since the propulsor produces drag over and above the bare hull drag.

Now if

$$\frac{T(1-t)V/550}{P_D} = \eta_{pump} \times \eta_{jet} \times \eta_S \times \eta_{h/i} \qquad [7]$$

$$\frac{T(1-t)V/550}{P_D} = \frac{\rho gQH/550}{P_D} \times \frac{V}{V+\frac{\Delta V}{2}} \times \eta_S \times (1-t) \qquad [8]$$

where T = craft thrust,

V = craft velocity, and

$\Delta V = (V_j) - V$.

But equivalence of the left-hand and right-hand sides of the equality can better be visualized if the pump efficiency

$$\frac{\rho g Q H/550}{P_D} \quad \text{is written as} \quad \frac{T_p V_p/550}{P_D}$$

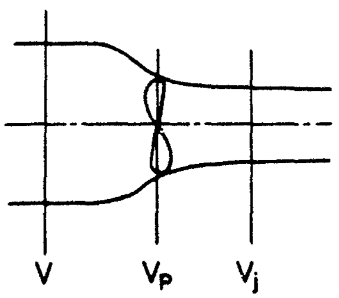
Solving for η_S

$$\eta_S = \frac{\dfrac{T(1-t)V/550}{P_D}}{\dfrac{T_pV_p/550}{P_D}\left[\dfrac{V}{V+\dfrac{(V_j-V)}{2}}\right](1-t)} = \frac{\dfrac{T(1-t)V/550}{P_D}}{\dfrac{(T_pV_p/550)(1-t)}{P_D}\left[\dfrac{V}{\dfrac{V}{2}+\dfrac{V_j}{2}}\right]}$$

Cancelling like forms

$$\eta_S = \frac{T}{\dfrac{T_pV_p}{\dfrac{V}{2}+\dfrac{V_j}{2}}}$$

Now for a simple pump (ducted propeller)



Pump Velocity Schematic

$$V_p = V + \frac{(V_j - V)}{2} = \frac{V}{2} + \frac{V_j}{2}$$

and

$$T_p = T$$

Therefore

$$\eta_S = \frac{T}{\dfrac{T\left(\dfrac{V}{2} + \dfrac{V_j}{2}\right)}{\dfrac{V}{2} + \dfrac{V_j}{2}}} = 1$$

indicating that η_S is chosen to be independent of the external intake and jet conditions.

R = T(1-t) by definition where t = thrust deduction.

Therefore

$$\eta_{hull/inlet} = (1-t) \qquad [9]$$

The result is

$$\eta_{D_{waterjet}} = \eta_{pump} \times \eta_{jet} \times \eta_{system} \times (1-t) \qquad [10]$$

The determination of true η_D for a waterjet-propelled craft requires a series of experimental tests of bare hull, appended, and self-propelled conditions. This will be discussed later under the section on model and prototype testing. However, in regard to propulsion efficiency, the references pertaining to experimental evaluation (boat tests)[3,14-17]

provide data on η_T. Only Reference 16 attempts to correct jet thrust to effective thrust with the reduction of thrust by inlet drag. Reference 18 is a report on a water channel test of a stationary waterjet propulsion system which also provides η_T results.

η_T is inadequate to completely describe the performance of a marine craft for the following reason. Conceivably, the magnitude of propulsor thrust for a particular propulsor can be large in comparison to the thrust of a second propulsor and, consequently, P_T would be high. However, a significant percentage of the propulsor thrust may be required to overcome the increased hull resistance which the propulsor itself adds to the bare hull resistance. Thus, it is possible to have a high propulsor P_T but, at the same time, a high P_S to propel the craft at design speed. Although the resulting η_T might be comparable with that of another propulsor or propulsion configuration, the P_S required could be considerably larger. This conclusion was borne out in waterjet system computer trade-off studies at Boeing.[19*] Consequently, if one is comparing various propulsion system installations on a particular craft, the most meaningful comparison parameter is P_S.

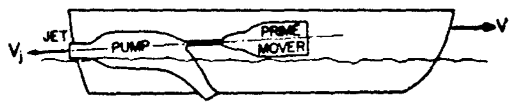
In several of the reports, an attempt is made to calculate a propulsive efficiency for a waterjet installation either as a product of pump, jet, system, and hull interaction efficiencies, or as a product of external, internal, and jet efficiencies. As far as overall waterjet propulsion system installations are concerned, momentum considerations are used in the majority of cases for performance prediction (see References 3, 4, 14, 19, 21-28).

*For further interesting information on this subject, refer to discussion of Reference 14 by Dr. C. Kruppa.

Use of Ideal Propulsive Efficiency (η_I)

Consideration of η_I can provide insight into the ideal performance of a particular waterjet system in stages of preliminary design.

The derivation of η_I, based on momentum theory with the assumption of one-dimensional flow and referring to the figure below, is as follows:



Schematic of Waterjet Installation

If it is assumed that $V = V_{craft} = V_{inlet\ water}$, η_I is defined as:

$$\eta_I = \frac{\text{power out}}{\text{power in}} = \frac{\text{work per unit time by thrust}}{\text{work per unit time by ideal pump}}$$

$$= \frac{P_O}{P_I} = \frac{(T \times V)550}{P_I} = \frac{\rho\ Q V_i\,(V_j - V_i)}{\frac{1}{2}\rho Q[V_i + (V_j - V_i)]^2 - V_i^{\,2}} \qquad [11]$$

But $V_i = V$ and $V_j - V_i = V_j - V = \Delta V$.

$$\eta_I = \frac{\rho\ Q\ V\ \Delta\ V}{\frac{1}{2}\rho Q\ (V^2 + 2\ V\Delta V + \Delta V^2 - V^2)} = \frac{V\ \Delta\ V}{V\Delta V + \frac{\Delta V^2}{2}}$$

$$\text{Ideal Jet Efficiency } \eta_I = \frac{2\,V\Delta V}{2\,V\Delta V + \Delta V^2} = \boxed{\frac{1}{1 + \frac{1}{2}\frac{\Delta V}{V}}} \qquad [12]$$

The ideal jet efficiency η_I can also be conveniently expressed in terms of the propeller thrust coefficient defined as

$$C_{T_p} = \frac{T_p}{\frac{1}{2}\rho\ V^2\ A_p}$$

since

$$T_p = A_p \times \frac{1}{2}\rho\,(V_j^2 - V^2)$$

then

$$\eta_I \text{ which} = \frac{T\,V_o}{P_I} = \frac{2}{1 + \frac{V_j}{V}}$$

Now

$$\boxed{\eta_I = \frac{2}{1 + \sqrt{1 + C_{T_p}}}} \qquad [13]$$

which indicates that η_I depends only on the propeller load coefficient.

The expression for Ideal Jet Efficiency η_I, Equation [12], indicates that a maximum efficiency exists for a specified system loss at a particular value of pump head or of the velocity ratio. If for high jet propulsion efficiency a low $\Delta v/v$ is adhered to, one must be satisfied to pump a large quantity Q (rate of flow in CFM or GPM), because $T = \rho Q \Delta v$. A high Q through a pump requires either high flow velocity or large flow passages. The latter is advantageous as far as keeping pump pressure losses low; however, large pump dimensions mean a high fluid weight in the pump. Thus, compromise, adjusting to optimum conditions for a specific pump application,

is required.

Real System Propulsive Efficiency

It can be seen from the derivation of Equation [12] that η_I is dependent on the ratio of jet velocity (nozzle exit velocity) V_j to ship velocity V. If the jet efficiency is calculated for the case where the thrust and velocity developed are again a measure of the power out, but where the power in is increased to overcome real system loss, and if no assumption about the internal system head loss is made, the following approach can be taken:

Total loss = inlet duct loss + exit duct and nozzle loss

$$h = hi + he$$

The pump output power P_{pump} can be written by kinetic energy:

$$P_{pump} = \frac{1}{2}\frac{w_1}{g}(V_j^2 - V^2) + W_{hi} + W_{he}$$

where w_1 = weight of water/unit time.

Therefore

$$\eta_{jpr} = \frac{2\frac{w}{g}(V_j - V)\ V}{\frac{w}{g}(V_j^2 - V^2 + 2gh)} = \eta_I \times \eta_{system}$$

$$= \frac{2(V_j - V)V}{V_j^2 - V^2 + 2gh} = \frac{2(V_j - V)\frac{V}{V^2}}{\frac{V_j^2}{V^2} - \frac{V^2}{V^2} + \frac{2gh}{V^2}}$$

$$\eta_{jpr} = \frac{\frac{2\,(V_j - V)}{V}}{\frac{V_j^{\,2}}{V} + \frac{2gh}{V^2} - 1} = \boxed{\frac{2\,(k - 1)}{k^2 + \frac{2gh}{V^2} - 1}} \qquad [14]$$

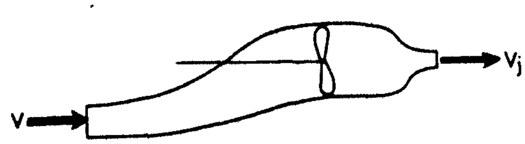
= real jet efficiency

where $k = V_j/V$ = jet velocity ratio.

Although any estimated or assumed system losses should be verified by experimental determinations, the establishment of probable ranges of waterjet efficiency can be looked at by making preliminary estimates of component losses, and toward this end, it is interesting to make a comparison of expressions for waterjet system efficiency of real systems as proposed by Levy,[21] Johnson,[24] and Hatte-Davis.[19]

Assuming $H_L = K_A \frac{V_j^{\,2}}{2g}$

$$\eta_{jpr_{Levy}} = \frac{2\,(k - 1)}{k^2(1 + K_A) - 1} \qquad [15]$$



where $k = V_j/V$,

V = craft velocity,

V_j = jet velocity relative to craft,

H_L = system head loss, and

$$K_A = \frac{H_L}{\frac{V_j^2}{2g}}$$

According to Johnson:

Assuming $H_L = K_B \frac{V^2}{2g}$

$$\eta_{jpr_{Johnson}} = \frac{2(k-1)}{k^2 - 1 + K_B} \qquad [16]$$

According to Hatte-Davis:

$$H_L = \left[K_2 k^2 + \left(\frac{1}{k-1}\right)^2 (DLF)\right] \frac{V^2}{2g}$$

$$\eta_{jpr_{Hatte\text{-}Davis}} = \frac{2(k-1)}{k^2(1+K_2) - 1 + \left(\frac{1}{k-1}\right)^2 DLF} \qquad [17]$$

where K_2 = nozzle loss coefficient and DLF = duct loss factor.

The Hatte-Davis expression[19] for η_{jpr} is based on an approach wherein the inboard losses are not lumped together and are not made proportional to either inlet velocity or jet velocity, as is the case of the Levy or Johnson approach, constraints which are considered unrealistic. Thus, it is suggested that for jet efficiency of a real system, Expression [17] should be used in preference to the others for advanced studies.

A type of plot of jet efficiency versus velocity ratio for various values of the system loss coefficient K_L, which is familiar in jet propulsion technology,[26] is shown below (Figure 1).

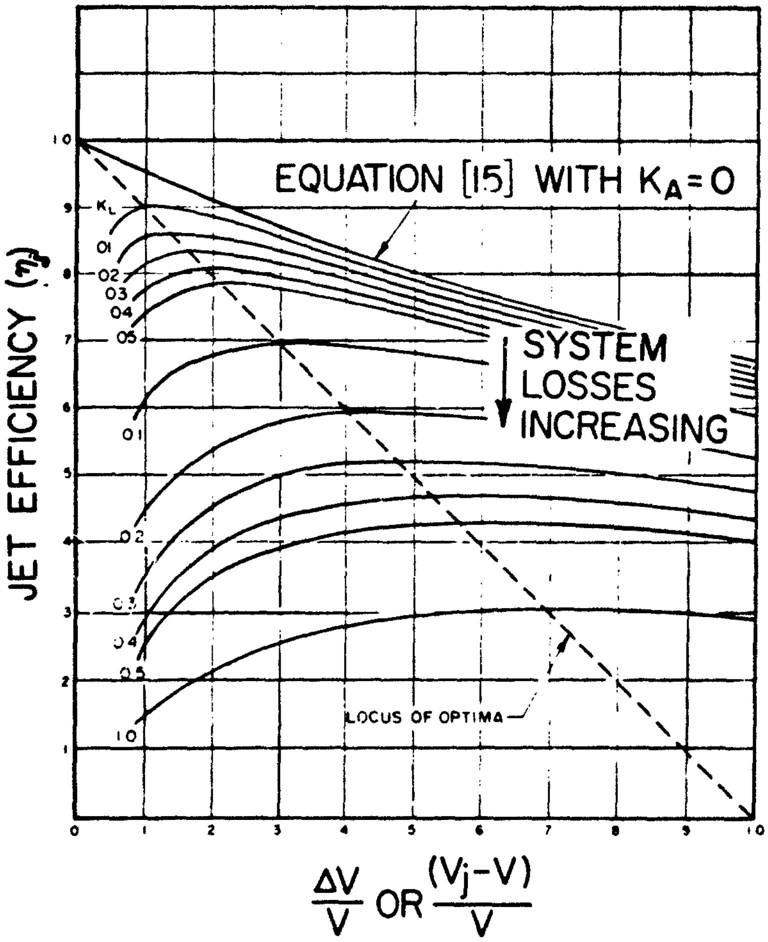


Figure 1 - Effect of System Losses on Optimum $\frac{\Delta V}{V}$

Once the η_{jpr} is obtained, it must be multiplied by η_{pump} in order to yield the propulsive efficiency of the overall propulsion system. The accuracy of prediction of the propulsive efficiency by the above methods can be no better than the accuracy of the loss coefficients used in the calculations.

Comparison of Ideal Propulsion and Ideal Propeller Efficiencies

One other interesting area pertinent to this discussion is the relationship of Ideal Propulsive Efficiency and Ideal Propeller Efficiency. It is interesting to note that the uppermost curve of Figure 1 is a plot of Ideal Propeller Efficiency (propeller without viscous and rotative losses).

By simple momentum theory

$$\eta_I = \frac{1}{1 + \frac{1}{2}\frac{\Delta V}{V}} \qquad \text{[12] repeated}$$

By referring to Figure 2, it can be seen that this can be written as:

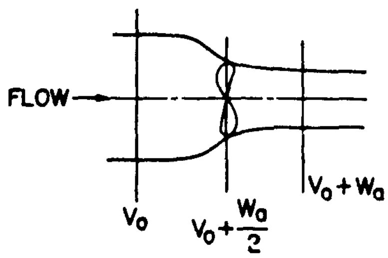


Figure 2 - Propeller Velocity Schematic

$$\eta_I = \frac{1}{1 + \frac{1}{2}\frac{\Delta V}{V}} = \frac{1}{1 + \frac{1}{2}\frac{W_a}{V}}$$

$\eta_{I_{propeller}}$ can also be derived from a consideration of the velocity vector diagram for a blade element.[70]

Some confusion may exist in reference to magnitude of comparative hydrodynamic performance of propellers and waterjets as applied to

high-speed hulls. Certain statements existing in the literature[4] imply that propeller efficiency drops off at high speed while waterjet efficiency increases. Such arguments tend to neglect the fact that supercavitating propellers whose hydrodynamic efficiencies do not degrade with increased speed should be utilized in the supercavitating speed range. It is known that performance of a subcavitating propeller will fall off as speed and loading increase, and knowledgeable designers would not attempt to use it at high speed. The actual reason for performance of some supercavitating propellers to be less as speed increases is that optimum blade geometry has to be sacrificed due to structural problems in overstressing the material. No positive indication has been given to show that "long life" high-speed pump impellers will not face the same problems.

Summary

This then is an attempt to show how thrust efficiency η_T compares to η_D as a performance parameter and, further, to explain why η_T is so often found in use in the waterjet literature (although it is usually misnamed). Its limitations should be recognized, however, and the extent to which predictions of "propulsive efficiency" based on simple momentum jet efficiency calculations tempered with estimated system losses should be carefully controlled.

Some type of analytical treatment can be applied to a prediction of performance of each major component of a waterjet system, i.e., the pump, inlet, etc. Some of the references present analyses (in varying degrees of complexity) of the performance of system components and compare the results with experimental data; e.g., Reference 20 on impellers.

By far, however, the bulk of the available theoretical work included in the present literature relies on simple momentum considerations of ideal jet efficiency and, further, real system efficiency by introduction of system losses obtained from experimental, empirical, or "crystal ball" sources.

The inherent limitations in the use of thrust efficiency, even when measurement of the variables included in η_T is very accurate, should be recognized. Further, P_T magnitudes can vary depending on whether thrust

is jet thrust (often calculated from measured momentum variables of mass flow and jet and inflow flow velocities) or actual effective propulsion reaction thrust. The authors of Reference 17 attempted to measure reaction thrust using pump-mounted load cells in their boat-testing program.

In summarizing the discussion of the problems involved with the efficiency of propulsion, the following points appear to be significant:

1. Meaningful propulsion efficiency evaluation for waterjets should, as in the case of more conventional propulsion, involve determination of η_D. $\eta_{D_{waterjet}}$ is given by Equation [10] and $\eta_{hull/inlet\ interaction}$ by Equation [9]. When circumstances require the determination of the propulsion system component efficiencies, as in the case where performance improvement or research is the goal, η_D broken down in this way is a satisfactory parameter.

2. η_D provides more definitive information than does η_T in a performance comparison of two different propulsors applied to a particular hull. A familiar example here is the comparison of a waterjet with a conventional propeller. If R is chosen to be the bare hull towed resistance (i.e., without any propeller system appendages or, on the other hand, waterjet inlet or exhaust ports), then a ratio of η_D's turn out to be simply a ratio of P_S's at any particular speed. As pointed out earlier, a comparison of η_T for the two systems would not be a valid indication of relative propulsion efficiencies.

3. Ideal jet efficiency and ideal propeller efficiency are shown to be mathematically equivalent. In both cases, corrections must be made for losses in order to achieve the actual efficiency of a propulsor. Since the waterjet, by design, has more sources of losses than the open propeller, it is generally less efficient.

4. Accurate predictions of waterjet propulsion efficiency will generally not be obtained by applying estimated or empirical system loss performance data to a jet efficiency figure calculated by simple momentum theory.

THE WATERJET PUMP

The pumping machinery is a very important component of a waterjet system. Proper design of the pump requires not only a thorough understanding of the general characteristics of various type pumps but, in addition, requires the waterjet propulsion pump design to be in accord with the design of all the other components of th: propulsion system. The scope of this report permits only a brief coverage of the subject of pumps for waterjet application. An attempt is made to put forth the major considerations of pump requirements and characteristics (which are treated in References 2, 21, 22, 23, and 24) along with some discussion of performance criteria. There is much published literature on pump research and application. The references cited herein do not form a complete list but are given with the intention of guiding the reader to pump literature.

The function of the pump in a waterjet system is to accelerate the surrounding fluid medium or increase the energy of the flow, thereby producing thrust. This, of course, is also the function of an open or ducted propeller.

From the section of the report on propulsion efficiency, it will be remembered that the optimum jet velocity ratios corresponding to practical waterjet system efficiencies are relatively low. Thus, a pump having characteristically high mass flow rate and low head performance is a major requirement for efficient operation. However, a high-speed pump will keep the duct size and weight of the waterjet small.

The types of pumps (broadly classified under turbo-machinery) utilized by various experimenters and propulsion system designers of waterjet systems include:

1. centrifugal (radial flow) - high head,
2. mixed flow - intermediate head, and
3. axial flow (propeller) - low head.

Waterjet systems may employ one or more pumps for each separate ingestion and discharge ducts. Several pumps used in series or in a multi-stage pump cause the same mass flow to be handled by each stage, but the head increases with each succeeding stage, and rpm is lower than that required

by a single stage. In a parallel pump design, each pump develops the aame head but the flow is shared. These pumps could be of the same type as a single large pump but would have a higher rotative speed. Parallel pump arrangements usually require complex plumbing systems.

The type of pump depends on the required pump head and flow rate which are determined from the thrust and speed requirements of the craft. However, certain design innovations are usually required to adapt a design to specifically conform to a waterjet propulsion application. One major consideration here is the establishment of off-design conditions which will affect the cavitation performance of the pump. Pump cavitation becomes a major problem at two operating conditions for hydrofoil and planing-type hulls: (a) at or near takeoff* when the pump impeller is turning at a high rotative speed and the total inlet static head is low due to a low ram head and (b) at cruise or very high planing speed when the impeller tip speed is at its highest. This second condition corresponds to the conventional subcavitating propeller limiting speed condition, but in the waterjet case, control of the local pressure at the pump can delay cavitation inception.

The operating requirements of waterjet pumps for high-speed marine vehicle applications result in their cavitation parameters falling in the same range with cavitation characteristics of space rocket turbo-pumps. Consequently, work has been done in the development of waterjet pump impellers very similar in design to rocket pump inducers. It should be noted, however, that rocket pumps have limited life. This is not to say that all of the existing axial or mixed flow pumps now being used in waterjet systems employ inducer type impellers. The Buehler "turbopower" units and the Hamilton waterjet (from which both the Buehler and the British version Dowty-Hamilton designs were evolved) are examples of axial flow pumps employing multi-blade impellers, single and multi-staging being available. On the other hand, inducer type rotors are being developed by Curtiss-Wright[29] and Pratt-Whitney[30] Division of United Aircraft. In addition, other rocket pump manufacturers are experimenting with either subcavitating or fully cavitating inducer designs, especially suited to high-speed waterjet propulsion. The Aerojet General Corporation has developed a type of waterjet propulsion pump in which the pump casing or volute

* See Figure 3, page 35.

is made also to function as the jet nozzle with the idea of direct conversion of mechanical energy to jet kinetic energy with minimum conversion to potential energy first.[31]

A good percentage of the pump experimental research is being complemented with theoretical pump design approaches. The basic analytical methods follow either a classical approach in which momentum relations are utilized (see References 2, 22, and 31) and textbooks (References 13, 32, 33, 34 and 35), or a procedure involving lifting-line or lifting-surface theory. Certain simple cavitation analyses can be made by applying cascade techniques (References 30, 36, 37, and 38) to a classical solution. For a more detailed consideration of blading and internal flow, however, lifting-line[37] or lifting-surface [20] approaches are useful.

Experimental work is being done on pumps especially designed for waterjet propulsion or on types whose characteristics make them suitable for possible waterjet application. As can be determined by considering Table 2, actual experimental pump hydraulic performance is reported in References 14, 15, 20, 29, 31, 36, 37, 38, 40, 41, 42, and 43. In addition, certain ones of these references contain cavitation data on the pump performance (References 14, 15, 29, 37, 38, 40, 41, 42, and 43).

Most of this testing has been performed in pump cavitation loop facilities in which impeller scaled models are used in the prediction of impeller performance. Such facilities usually provide a means for visual observation of cavitating phenomena. Several large-scale static pump test stands capable of supporting fairly high-power prototype waterjet pumps are now in operation; e.g., at Aerojet General Corporation[31] in Azusa, California, and at Pratt-Whitney Division in West Palm Beach, Florida.

It was stated previously that good waterjet propulsion pump design will vary from stationary type pump design[32,35,44] due to a difference in the basic requirements of the two machines. It is possible that, in like manner, the ideal terminology and performance coefficients utilized for many years in pump technology are not ideal or optimal for the technology of waterjet propulsion pumps.[33] In addition, values of performance coefficient limits published in reference sources, e.g., Standards of the Hydraulic Institute,[45] should be reanalyzed in light of new pump technology. A short analysis based on the pump and waterjet pump performance parameters,

dimensional analysis, and a comparison with those coefficients used in propeller technology follows.

At corresponding points in the full-scale (or large-scale) and model flows, the flow should be geometrically and dynamically similar.[46] Relating the pressure differences through a simple pump to the pertinent variables, it is assumed that significant pressure differences in the pump are produced by mass forces of the fluid, and the following relationship between the variables is obtained.

$$\frac{P}{\rho V^2} = \frac{Nd^3}{Q}$$

Thus, it is apparent that a definite relationship between the pressure rise and the rate of flow must exist if dynamic similitude of the hydrodynamic pump action is maintained from prototype to model. In pumps, pressure rise is usually spoken of in terms of head.

However, viscosity cannot be neglected in the case of pumps; it is a more important consideration here than in the case of open propellers. The ability of a pump to develop thrust T can be thought of as being achieved through the pumphead rise H and the volume flow rate Q. The head is dependent on the density ρ and viscosity μ of the pumped fluid, the volume flow Q, the impeller diameter d, and rotation speed N. By treating the product gH (g being acceleration due to gravity) as the dependent variable and assuming

$$gH = f_1\ (\rho, \mu, Q, d, N)$$ [13]

dimensional analysis, as used above, reduces this function to the simpler dimensionless relationship:

$$\frac{gh}{N^2 d^2} = f_2 \left(\frac{Q}{Nd^3}, \frac{\rho N d^2}{\mu} \right)$$

These three dimensionless groups are termed head coefficient K_h, flow coefficient Φ, and Reynolds number R_e, respectively. The choice of certain performance parameters in propeller and pump work rests mainly on convenience. In propellers, V and T are easy to measure, whereas in pumps, Q and H are more readily determined. For a propeller, a brief review of the performance parameters usually used may be in order.

$$T = K_T \rho N^2 d^4 \qquad [18]$$

and

$$P_S = \frac{2\pi N K_{torque} \rho N^2 d^5}{550}$$

$$\eta_{propeller} = \frac{P_T}{P_S} = \frac{K_T}{K_{torque}} \left(\frac{J}{2\pi}\right) \qquad [19]$$

where

$$\frac{V(1-w)}{Nd} = J$$

On the other hand, slightly different performance coefficients turn out to be the most useful for pump performance evaluation:

$$\eta_{pump} = \frac{\text{pump hp}}{P_S} \qquad [20]$$

$$P_P = \frac{\rho g Q H}{550}$$

$$P_S = \frac{2\pi N \text{ Torque}}{550}$$

where Torque = $K_{torque}\, \rho N^2 d^5$.

Now P_P and P_S can be related to the dimensionless head, flow (as derived from the dimensional analysis), and torque coefficients, respectively, just as in the case of a propeller.

Thus

$$P_P = \frac{\rho g Q H}{550} = \frac{\rho Q \cdot gh}{550}$$

where

$$gH = K_H N^2 d^2 \quad \text{and} \quad Q = \phi N d^3$$

Therefore

$$P_P = \frac{\rho \phi N d^3 \cdot K_H N^2 d^2}{550} = \frac{\rho \phi K_H N^3 d^5}{550}$$

Likewise

$$P_S = \frac{2\pi N \cdot K_{torque}\, \rho N^2 d^5}{550}$$

Therefore, dividing P_P by P_S,

$$\eta_{pump} = \frac{P_P}{P_S} = \frac{\rho \phi K_H N^3 d^5}{550} \left(\frac{550}{2\pi N K_{torque}\, \rho N^2 d^5} \right)$$

$$\eta_{pump} = \frac{\phi K_H}{2\pi K_{torque}} = \boxed{\frac{K_H}{K_{torque}} \cdot \frac{\phi}{2\pi}} \qquad [21]$$

where

$$\phi = \frac{Q}{Nd^3} \quad , \quad K_H = \frac{gh}{N^2 d^2}$$

Thus it can be seen by comparing [19] and [21] that

$$\eta_{propeller} = \frac{K_T}{K_{torque}} \cdot \frac{J}{2\pi} \qquad [19] \text{ repeated}$$

$$\eta_{waterjet\ pump} = \frac{K_H}{K_{torque}} \cdot \frac{\phi}{2\pi} \qquad [21] \text{ repeated}$$

Later it will be shown that η_{pump} can be written in a form which when multiplied by the jet nozzle efficiency η_j is physically equivalent to $\eta_{propeller}$. For propeller performance evaluation, K_T and K_Q are usually plotted against J. For a waterjet pump, K_H and K_Q could be plotted against ϕ or against V_j/V, the jet velocity ratio if the pump is running in a moving craft.

The major deviations in the use of these specialized performance coefficients occur because pump and propeller engineers utilize the performance variables which are most easily measured in their respective tests. Many variations in parameters could be derived from the basic variables as measured.

Pump designers for many years have used a parameter termed "specific speed" which originally was introduced by a German, R. Camerer, in 1915 for describing the hydraulic type of water turbines. Each of the three types of pumps mentioned above covers a range of specific speeds N_S, and attains its maximum efficiency at a point somewhere in this range, efficiency dropping off on both sides of this particular specific speed. Geometrically similar pumps of different sizes will have similar head flow performance characteristics if operated at the same specific speed (assuming viscous effects are small). N_S is a number which is proportional to impeller rotative speed and rate of flow and inversely proportional to

pump head rise. Unfortunately, it is usually used in a form which has not been made dimensionless, a factor causing some confusion in pump research work. Despite this, it is a very useful parameter for comparing performance of different pumps or of pumps with their models. Specific speed involves only the pump operating conditions by means of eliminating impeller diameter between the head and flow coefficients. By the provision that rotational speed be a linear variable, specific speed can be obtained as:

$$N_S = \frac{NQ^{1/2}}{H^{3/4}} \tag{22}$$

This form is not dimensionless but, by utilizing gH as the term in the denominator instead of H, a dimensionless form of specific speed is:

$$\text{dimensionless } N_S = \frac{NQ^{1/2}}{(gH)^{3/4}} \tag{23}$$

Addision[33] suggests that the dimensionless form of specific speed be called characteristic shape number to distinguish it from the more common form, and the word shape is appropriate because modelling of the pump requires geometric similarity or, in other words, retention of pump shape.

By substitution of the coefficients ϕ and K_H into [23], N_S can be written as:

$$N_S = \frac{\phi^{1/2}}{K_H^{3/4}} \tag{24}$$

If it would serve any useful purpose, a "characteristic shape number" could likewise be defined for propellers as:

$$N_S = \frac{J^{1/2}}{K_T^{3/4}} \qquad [25]$$

but the need for such a parameter is not apparent.

Another point of interest, alluded to earlier, which arises when comparison of propeller and pump performance efficiencies are attempted is exemplified by the case of a ducted propeller for which efficiency has been calculated by, first, a propeller efficiency philosophy and, second, by a pump efficiency philosophy. The difference occurs in the use of different velocities in the expression

$$\eta_p = \frac{T \cdot V}{550} \div P_D \qquad [26]$$

For the propeller $V = V_a$, propeller advance speed; for the axial flow pump, V_d = velocity inside the duct.

Since the induced velocity inside the duct causes the pump flow velocity to exceed free-stream velocity, the "apparent" efficiency of the pump will be higher. Figure 4 shows a set of comparative efficiency curves for a ducted propeller,[47] calculated by the two methods and showing a significant difference in magnitude.

Note that $\eta_{propeller}$ and η_{pump} are only different by the difference in V_a (speed of advance) and V_d (speed of flow at propeller disk).

$$V_d = V_a + \frac{w_a}{2}$$

where w_a = total axial induced velocity component or ΔV.

$$\eta_{propeller} = \frac{\frac{TV_a}{550}}{P_S} \qquad [27]$$

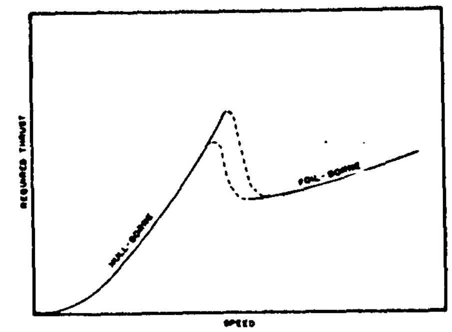


Figure 3 - Typical Thrust-Speed Relation

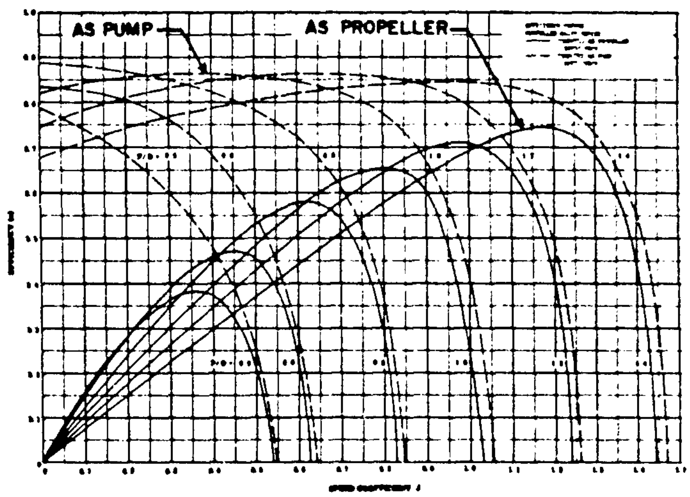


Figure 4 - Efficiency of a Ducted Propeller Calculated by Two Methods

$$\eta_{pump} = \frac{\frac{TV_d}{550}}{P_S} = \frac{\frac{T\left(V_a + \frac{\Delta V}{2}\right)}{550}}{P_S} \quad [28]$$

$$\frac{\eta_{propeller}}{\eta_{pump}} = \frac{V_a}{V_a + \frac{\Delta V}{2}} \quad [29]$$

where

$$\frac{V_a}{V_a + \frac{\Delta V}{2}} = \eta_{jet}$$

Cavitation will play an extremely important role in waterjet propulsion pumps. Cavitation may affect the pump hydraulic performance as severe cavitation will cause pump erosion and degradation of pump performance. Because waterjet propulsion pumps will, at times, be required to work at relatively low suction heads, cavitation of the pump impeller will be a problem.[37] One advantage which the axial flow pump possesses is that multi-staging of impellers can be used to reduce the tendency for the main load-carrying impeller to cavitate. The technique of utilizing an inducer stage in which the static pressure is increased with very little kinetic energy increase has been used. This provides a sufficiently high suction pressure to the main flow accelerating impeller stage to prevent blade cavitation. A comparison of cavitation inception criteria for pumps[35] and propellers now follows:

Since pumps are usually used to produce a pressure rise through the impeller, the Thoma cavitation parameter (σ_{Thoma}) defined as

$$\sigma_{Thoma} = \frac{\text{net suction head}}{\text{pump head produced}} \quad [30]$$

is in general pump usage. Here, net suction head

$$H_{sv} \text{ (or) npsh} = h_{atmospheric} + h_{depth} + \frac{V^2}{2g} \text{ in feet of water} \qquad [31]$$

in which V = the velocity in the flow approaching the pump. The Thoma parameter is dimensionless, and if its constancy indicates cavitation similarity, then increased pump head would require increased suction head.

In propeller work, the cavitation parameter or cavitation index normally used is defined as

$$\sigma = \frac{H_1}{V^2/2g} \qquad [32]$$

where H_1 = (absolute pressure at shaft centerline - vapor pressure of water) and V can be either free-stream velocity or the inflow velocity at the center section of the propeller. This approach is taken since propellers inherently are not used to produce pressure rise (potential energy) but rather kinetic energy.

For cavitation effect on propeller performance, K_T, K_q (torque), and efficiency versus J curves are obtained at various values of σ from tests conducted in a cavitation tunnel. These tests are in addition to the open-water performance tests.

In pump procedures a single cavitation parameter is used to relate the inlet flow conditions to the pump speed and head rise. This parameter is a direct extension of the specific speed N_S, and is defined as

$$S = \frac{NQ^{1/2}}{(gH_{sv})^{3/4}} \qquad [33]$$

where H_{sv} has replaced H. S is termed suction specific speed and, when defined in this way, appears to be a valid dimensionless parameter.

Note that the Thoma cavitation index σ_t is an expression which is dependent on the pump itself; specifically, it is the ratio of the net suction static head supplied to the pump to the pumping head actually

developed. Thus σ_t can be seen to be equal to the ratio of N_S and S or $\sigma_t = (N_S/S)^{4/3}$

In contrast, the propeller cavitation index σ_o is an expression dependent on the condition of the flow; specifically, it is the ratio of the static head of the water to the dynamic head of the free-stream flow.

However, σ can be expressed in terms of V_R (resultant). The use of V_R makes $\sigma_R = \dfrac{P_o - P_v}{\frac{1}{2}\rho V_R^2}$ analogous to pump σ_t.

Summary

In summary, the points pertaining to performance evaluation of waterjet pumps which should be reviewed are as follows:

1. Pump efficiency must be multiplied by η_j before direct comparison can be made with conventional propeller efficiency.

2. Pertinent performance parameters for waterjet pumps will include flow rate Φ, head coefficient K_H, and torque coefficient K_q, characteristic shape number (nondimensional specific speed) and a nondimensional form of suction specific speed. Pump-flow variables such as flow rate and head will continue to be measured, since they are more directly attainable than the variables commonly measured in propeller testing.

3. Cavitation number can be defined in various ways (this variation usually arising in propellers because of choice in where velocity is measured), but for propulsion pumps will probably be most meaningful if it is based on the ratio of suction head H_{sv} to head developed by the pump H_p.

WATERJET INLET

This section and the following section of the report deal with the intake of and the internal flow of water in the waterjet system. Waterjet propulsors require optimization from the inlet to the exhaust nozzle. As pointed out previously, it does not particularly pay to strive for a high system efficiency through low jet velocity unless system losses are also minimized (refer again to Figure 1). The attainment of low loss or high

efficiency flow transmission components is a prime goal. The system component losses which are involved consist of inlet/diffuser (which can run from 10 to 30 percent), internal ducting (2 to 10 percent), and nozzle (1 to 3 percent).* These loss values are usually expressed as percentages of the ram head $V^2/2g$. The ultimate goal of an R & D program, based on analytic and experimental testing of inlets, internal ducting systems and nozzles, will be the development of a system for a particular craft which will provide adequate water flow rate at the lowest overall loss coefficient without detrimental cavitation.

The inlet or scoop location depends on the hull and waterjet propulsion system configuration. Most hydrofoil waterjet foilborne systems incorporate ram-type inlets mounted in the pod at the bottom of the strut.[24] Planing boat and displacement craft usually employ flush or scoop intakes in the hull bottom. Schemes have been proposed for side or bow located inlets (e.g., see U.S. Patent Office patent disclosures 2,884,889 and 3,188,997). The major design location considerations appear to be in keeping the vertical distances which produce elevation losses short, keeping the inlet in "green" water to prevent aeration, providing sufficient water flow to the pumps to produce the required thrust, and preventing or delaying the inception of cavitation. Good inlet system design requires low internal losses and high resistance to cavitation during the takeoff mode and low external drag during cruise. From a takeoff mode cavitation consideration, the critical parts of the inlet are the scoop (water entrance) and the transition from the inlet to the diffuser duct. The scoop obviously must capture the free-stream flow efficiently under a range of operating conditions between takeoff and cruise.

During takeoff, the ratio of inlet to free-stream velocity is high (pressure levels in the scoop are low), and internal cavitation is the primary concern. During cruise, on the other hand, this velocity ratio is relatively low (pressure levels in the scoop are thus relatively high),

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*The magnitude of the loss coefficients stated here are estimates representative of a range covering typical planing hull, CAB, and hydrofoil waterjet systems. A sharp bend just behind the inlet and long vertical strut duct, as is required for a hydrofoil craft, produce higher losses.

and resistance to internal cavitation is therefore high. But in the cruise mode, susceptability of external lip cavitation may be a significant factor.[19]

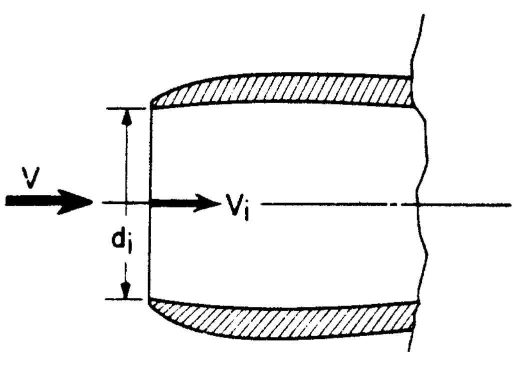
The net effect of cavitation in and around the inlet is two-fold. Cavitation can produce significant erosion (cavitation damage) of the inlet material; however, the more important consideration is degradation of pump performance due to excessive inlet/diffuser head loss and, ultimately, complete choking of the flow which starves the pump.

From a momentum exchange standpoint, the relationship of thrust required and inlet area is:

$$T = \rho A_i V_i (V_j - V_i)$$

where

$$A_i = K_s d_i$$



Letting $m = \frac{V_j}{V_i}$ (jet velocity ratio)

$$T = \rho A_i V_i (mV_i - V_i)$$

or

$$T = \rho A_i V_i^2 (m - 1) \qquad [34]$$

For a fixed geometry exhaust nozzle, m is fixed, thus A_i and V_i, which are interdependent, are the only controllable parameters for varying the thrust.

Variable geometry inlets could be used to assure sufficient flow to the pump at low ram-head speeds (takeoff) and allow the pump to work at its best point of design over a fairly broad range. However, the mechanical complexity of such an inlet in a sea water environment and cavitation problems of the fairing appear to be significant.

Definitive evaluation of inlet performance involves the determination of: (1) how efficiently the water can be "captured," over what range of velocities inlet cavitation will not significantly degrade this "capturing," and (2) how much the hull drag is affected by the presence of the inlet. A brief analysis of the pertinent parameters required in model scaling of the hydrodynamic forces on submerged bodies is given later under the section on model testing.

Now from a consideration of what useable work is available from the literature, it is noteworthy that examples of both older published empirical information reviewed for waterjet inlet application and some original new analytic approaches to the problem exist. The theoretical work, for the most part, involves attempts to predict the effects of the flow field impinging on the inlet by calculating the pressure distribution in the external and internal areas adjacent to the inlet lip. These particular analyses do not yield the inlet loss coefficient but serve to aid in lip and entrance angle design.

Methods currently in use are based on solutions to the potential flow problem, both linearized and nonlinearized techniques now existing. A two-dimensional method utilizes a distribution of sources on the mean camberline of the lip (see Reference 48). A more general result applying to the nonlinear problem can be achieved with a distribution of sources along the surface of the model. An example of this is the Douglas-Neumann type of approach applied to arbitrarily shaped inlets (References 22, 49,

and 50).

When the pressure distribution is available from one of the above techniques, it is very useful in affirming the character of the streamline flow and shows whether smooth or sharp peaks exist in the pressure distribution which could indicate separating flow. However, viscosity effects are not included as part of the potential flow solution and viscous effects must be considered by corrections, based on empirical data, being made to the potential flow results.

It seems practical to also utilize the portions of existing empirical data which are considered reliable on marine condenser scoops[23,24,51-54] and aircraft oil cooler scoop testing,[55,56] especially in the preliminary inlet designs.

It is possible that some inlet designs (when considered integrally with a particular hull flow field) could be low in internal loss but have high external drag effects. A certain amount of experimental work is required in determining the net performance of such designs. References 14, 19, 22, 23, and 24 are valuable in pointing out means for system performance prediction using existing empirical data.

Practically all of the inlet studies carried out so far have been slanted toward hydrofoil inlet. The biggest present need is for comparable studies for flush planing hull scoops and ram or flush CAB sidewall-type inlets.

The amount of ram recovery or captured free-stream dynamic pressure through the inlet can be determined by measuring the characteristics of the water approaching and leaving the inlet. An inlet with poor flow will experience a large energy or head loss

$$\frac{V_1^2}{2g} + H_s$$

where H_s is the static head, which is atmospheric + depth head. This should be measured before and after the flow passes the inlet lip and turn/vane (if turn/vane exists).

Experimental data (Table 2) obtained in relatively recent testing

specifically regarding waterjet propulsion system inlets can be found in References 14, 16, 18, 22, and 57. The waterjet propulsion systems reported in Reference 14 employ dual wake intakes in order to provide a more uniform inflow to the pump. The work reported by Lockheed in Reference 22 was obtained from hydrofoil craft ram-type model tests in the Lockheed Underwater Missile Facility (LUMF) at Sunnyvale, California (variable-pressure towing basin). The data of Reference 57 were obtained from scale-model inlet tests of a strut-type inlet in the Hughes Aircraft (Tool Division) free-jet facility at Los Angeles.

The quantities or variables normally measured in experimental inlet studies include: craft velocity V, inlet velocity V_i, inlet geometry (lip, angle, size), guide vane geometry, static pressure, pressure distribution, and velocity profiles. From these data the following typical parameters are derived:

> Pressure loss coefficient, velocity ratio (V_i/V), geometry, drag coefficient, pressure distribution, velocity profile, critical cavitation number (σ_c), and net positive suction head (npsh).

A method of displaying inlet performance is to plot the inlet loss coefficient K_{L_i} (as a percentage of free-stream velocity head) versus cavitation number for a family of inlet velocity ratios $\dfrac{V_i}{V_{\text{free-stream}}}$. This produces characteristic "break" curves of the type described in Reference 19 (see Figure 5).

Some inlet data instrumentation was available for the boat testing reported in References 3, 14, 15, 16, 18, and 58. These reports include a presentation of the data acquired. Note again that the Hydronautics tests (Reference 18) are from stationary model tests with moving flow.

Summarizing the areas discussed in this section points to the following high points:

1. The waterjet hull inlet is a critical area in regard to both external and internal flow performance.

2. Analytical methods exist which can greatly aid in the design of

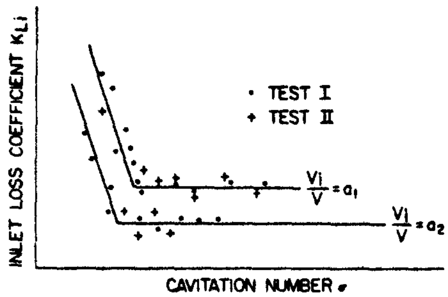


Figure 5 — Inlet Internal Performance

lips, inlet angles, etc., in predicting pressure distribution.

3. Inlets for craft which operate from a displacement to a planing condition may require variable geometry designs to accommodate both take-off and cruise requirements.

Takeoff — internal inlet can choke the pump due to cavitation.

Cruise — external inlet can cavitate, thereby increasing drag.

4. A good inlet should provide adequate flow, have low K_L, and be cavitation resistant.

Definitive inlet testing requires holding of Froude and cavitation numbers simultaneously.

Empirical condenser scoop and aircraft oil cooler scoop data are useful during preliminary design.

A quantity of hydrofoil (ram) inlet data is now available, and the need for CAB or planing boat-type hulls is evident.

WATERJET DUCTING

In a waterjet propulsion system, a certain amount of ducting must be installed to move the water from hull inlet to pump and from pump to exhaust nozzle. Hydrofoil boats with waterjet systems utilizing strut-pod inlets and deck-mounted pumps require a relatively extensive ducting arrangement. On the other hand, small planing boat installations can have very short connecting ducting, and most commercial waterjet propulsors incorporate inlet, diffuser, pump casing, and exhaust nozzle in only two or three castings. Captured air bubble craft will require waterjet ducting systems which are slightly more extensive than for planing boats but less than those for hydrofoil craft.

A number of system layout studies aimed at optimizing system designs have been made for specific type hull waterjet installations by Hydronautics for CABS,[59] and Pratt-Whitney Division for hydrofoil craft, air-cushion craft, and large displacement-type ships (destroyers).[60] In addition, Lockheed has published some system layout work,[22] and Reference 24 by V. Johnson of Hydronautics contains some hydrofoil craft ducting system layouts. Kim, in Reference 23, treats the problem of the tradeoff of benefits of single ducting versus multiple ducting systems, the relative importance of bends, straight lengths, vanes, etc.

The function of the duct is to deliver the correct quantity of water to the entrance of the impeller efficiently (with minimum pressure loss) and with a reasonably uniform velocity distribution, and to exhaust the water efficiently. The efficiency of the ducting system, as in any piping system, is dependent on the length of pipe, number and type of transitions, and pipe roughness. In general, a duct system should be light weight (including weight of water) and have low hydrodynamic loss. Considerations of low weight and vibration (structural and internal hydrodynamic) will not be dwelled upon here. The hydrodynamic losses which will be discussed here involve friction losses at internal ducting walls, mixing losses (pressure loss and friction loss) in areas where transitions such as enlargements, contractions, and turns exist, and velocity profiles at sections approaching the impellers and stator vanes. An example of a condition which might cause significant problems is that of the impeller shaft of an axial-type

pump passing through the supply duct causing nonuniformity to the impeller inflow.

The flow of an incompressible fluid inside a filled pipe or duct produces certain hydrodynamic forces. The significant forces in this case are: inertial, gravity, friction (viscous), and pressure. Surface tension as characterized by Weber number and compressibility by Mach number can be ignored for water flow in waterjet piping systems. It is common practice to use the following dimensionless parameters associated with the above forces:

$$R_e = \frac{\text{inertial}}{\text{viscous}} = \frac{\rho V \ell}{\nu} \text{, Reynolds number}$$

$$F_n = \frac{\text{inertial}}{\text{gravity}} = \frac{V^2}{g\ell} \text{, Froude number}$$

$$C_p = \frac{\text{inertial}}{\text{pressure}} = \frac{1}{\text{pressure coefficient}} = \frac{\Delta p}{\frac{1}{2} V^2}$$

$$= \frac{p_\infty - p}{\frac{1}{2}\rho V^2} \text{, pressure coefficient}$$

where ℓ = characteristic dimension, for pipes ℓ is the pipe diameter, and p = local static pressure.

The aforementioned dimensionless parameters provide a basis for establishing dynamic similitude of the flow in models of ducting systems. The geometric similarity between a prototype and model should extend to scaling the roughness of the internal duct wall. Nondimensionally, this would make relative pipe roughness (e/d) equivalent for model and prototype. Relative to the viscous and pressure forces which are produced, gravity forces are of minor consequence in the flow of fluid through a filled pipe. Consequently, Froude number can usually be ignored in model studies of this type. However, in certain instances Froude number may be of significance. Although this parameter is most often associated with free surface gravity effects on flow about bodies, it should be remembered

that to have the correct pressure coefficient or cavitation number over the vertical extent of a model, Froude scaling must be maintained. (See Appendix B.) Thus, in cases where the vertical dimension of the body is large relative to the depth of immersion, it may be necessary to consider Froude number in order to have the proper scaling of the pressure coefficient.

In the preliminary design stage of waterjet systems, use can be made of published empirical data on pressure loss coefficients of straight ducting, turns or elbows, vanes, nozzles, and other transitions. References 13, 22, 23, 24, and 34 are good sources of this type of data. Waterjet ducting losses are included in the system performance measurements obtained during the boat tests described in Reference 14 (British). References 50 and 61 by Gibbs and Cox, and Reference 60 by Arcand of Pratt-Whitney utilize published experimental ducting loss data in arriving at predictions of system efficiency. Johnson, in Reference 24, suggests some ranges of magnitude for system loss coefficients which are apparently based on published empirical data. The data available in these references are summarized in Table 2. It can be seen by studying such loss data that frictional resistance is more significant in internal waterjet systems than in the case of open or even conventional ducted propellers.

In summary, it appears that the ducting performance problem is less critical at the present time than that of the inlet. Published empirical loss data for piping and transition ducting can be used in making estimates of losses during system layout design. Performance tests of complete inlet and ducting systems, or models thereof, should definitely be conducted when high propulsion system efficiency is a requirement. Details of such testing are discussed below in the section on waterjet propulsion testing.

WATERJET PROPULSION TESTING

Performance Considerations

Experimental determination of the performance of either waterjet components or entire waterjet propulsion systems can be accomplished by application of the proper experimental techniques to tests of the prototype or scale model. In cases where prototype testing is impractical or

undesirable, model experiments will generally produce satisfactory performance data if geometric and dynamic similitude are maintained. The type and scope of the performance testing on a particular propulsion system will depend on the intended use of the data obtained. The requirements for most performance evaluations will fall into one of the following categories:

Type of Study	Requirements
1. Performance	Determination of the horsepower required to propel a particular craft at certain speeds. Also comparison of two or more propulsion system designs.
2. Design	Determination of the performance of various components of a system in order that the design of components may be improved so as to ultimately provide improvement in overall system performance.
3. Research	Determination of performance characteristics of system components in a systematic program of experimentation, but in which the components are not related to a particular design or system.

Performance testing of complete propulsion units under full-scale speed and load conditions finds wide application in the range of low horsepower waterjets. On the other hand, high-powered units requiring high efficiency and reliability necessitate the expense of constructing models and using specialized testing facilities such as variable-pressure water channels, high-speed towing basins, and cavitation tunnels. Several static waterjet test facilities[31] have been put into operation by industry. Regardless of whether testing is accomplished on a prototype or model,

certain performance parameters presented in the previous discussions on pumps, inlets, and ducting are required to characterize performance. Table 1, which appears on the following pages, is intended to present the pertinent parameters which characterize hydraulic performance and to list the measurements required in evaluating such parameters for the components of a waterjet system.

Table 1 should be used as a testing guide. Straightforward performance evaluations (study Type 1) on prototype craft may require only a limited number of measurements such as ship speed, payload, shaft horsepower, and fuel consumption. On the other hand, performance evaluations aimed at the achievement of high performance designs (study Type 2) will require the acquisition of most of the measurements and parameters listed in Table 1. In most cases, such measurements can be made while testing components or systems either as prototypes or scale models. In general, experimental data are more difficult to obtain in dynamic testing than in static testing. However, all of the suggested data have been obtained successfully in tests of prototypes and models of waterjet-propelled craft. These include photographic data on cavitation phenomena at the hull inlet.

The use of an accurately measured jet velocity for calculation of waterjet thrust from measurements of the system mass flow rate is, in general, a satisfactory means for obtaining thrust. The additional measurement, during trials, of the propulsor reaction thrust by means of, for example, pump support load cells is helpful in cases where very precise performance determination is required. Assurance that the direction of the jet reaction is collinear with the path of the boat is sometimes in question. In addition, it should be kept in mind that waterjet thrust will generally have to exceed towed hull drag by an amount equal to the additional drag induced by the propulsion system flow.

Model Testing

The principle of model testing is based on the prediction of prototype performance from models by judicious application of various scaling parameters. The previous sections on pumps, inlets, and ducting contain the development of the scaling parameters which should be considered in

TABLE 1

Pertinent Parameters that Characterize Hydraulic Performance

Type Testing	Measurement	Range	Derived Performance Parameters	Function
Pump static	Net positive suction head (H_{sv}),* static pump head, flow rate, rpm, shaft torque, impeller inflow, static thrust, velocity distribution. Also, if pump intake pressure is controllable, cavitation effect on performance, cavitation breakdown.	Design range.	Flow coefficient (ϕ), head coefficient (K_H), torque coefficient (K_q), $\eta_{impeller}$, η_{pump}, specific speed (N_S), suction specific speed (S), Thoma cavitation number (σ_t).	Static pump performance and mechanical reliability, cavitation breakdown.
Pump dynamic	H_{sv}, pump head, flow rate, rpm, cavitation observations under transient intake flow conditions.	Design rpm range, range of inlet velocity ratio (V_i/V), range of exhaust nozzle areas.	Same as above.	Overall system performance and reliability under real environmental conditions.
Water hull-inlet dynamic	Head loss (pressure drop), cavitation inception speed, inlet velocity ratio (V_i/V), inlet drag, inlet pressure distribution, visual cavitation observations, prediffusion and boundary layer ingestion.	Hi-Suction/Low head at takeoff to maximum ship speed or cruise and dash condition.	Inlet velocity ratio (V_i/V), cavitation number (σ), inlet loss coefficient (K_{Li}).	Optimization of inlet geometry to provide required flow, low internal losses, low drag, high cavitation resistance.

*Net positive suction head (H_{sv}) is equivalent to the total static head at the pump entrance.

Table 1 (Continued)

Type Testing	Measurement	Range	Derived Performance Parameters	Function
Internal intake ducting	Head loss, flow velocity profiles, cavitation observations.	Over speed range.	Duct loss coefficient (K_{Ld}).	Optimization of size and geometry for pump inflow velocity profile and minimum duct losses.
Internal exhaust ducting	Head loss.	Over speed range.	Duct loss coefficient (K_{Ld}).	Optimization of size and geometry for minimum duct losses.
Nozzle	Head loss.	Over pump speed range or jet velocity ratio (V/V_j), over range of nozzle exit areas.	η_j	Optimization of size and geometry for optimal nozzle-pump matching.

the evaluation of each component when modelled. In some cases, it is not possible to simultaneously maintain equivalence of all the scaling coefficients which might be applicable to a particular component.

Pump models should be tested at the specific speed N_S, suction specific speed S, and Thoma cavitation number σ_t of the prototype to assure that dynamic similitude at corresponding points in the model and full-scale flows is achieved. However, experience in pump testing indicates that scale effects can produce significant correlation problems if the physical size of a model is very small relative to the prototype.[33]

Model testing of inlets can be satisfactorily accomplished by considering one or more scaling parameters, depending on the design and application for the inlet. The full-scale boundary layer existing at the inlet should be modelled when definitive model experiments are conducted. It is shown in Appendix B that similarity of the pressure coefficient and thus the cavitation number at all points of the inlet flow will require Froude scaling in addition to maintaining the cavitation number of the prototype. This is important when the vertical dimension of the inlet is large relative to the depth of submergence or dynamic head, or when it is desired to scale the pressure gradient in a diffusing inlet. The internal inlet flow depends primarily on testing above a critical Reynolds number. In internal flow, it is apparent that the duct wall frictional stress τ_o is dependent on Reynolds number and relative pipe roughness coefficient (e/d).

Eventually, complete systems or subsystems must be built and tested. Sometimes, components such as the inlet and the supply ducting are tested alone[19,22], and in other cases the entire waterjet system is performance tested in an open-sea test boat. Reference 22 by Lockheed presents results of inlet and ducting performance measured on one-tenth scale models of subcavitating and supercavitating hydrofoil boat strut ram induction systems tested in LUMF basin. Indications are that the inlet and turning losses are high relative to duct losses for this type of ingestion system. Reference 19 by Boeing describes cavitation inlet testing on one-half scale-model ram-induction systems on the hydrofoil test craft LITTLE SQUIRT. Ducting losses are included in these measurements. Extensive instrumentation must be installed in the ducting system to separate the various losses produced by the inlet, the diffuser, the pump, and the other components of

the system.

Testing a Waterjet System

There are a number of alternate methods of performance testing a complete waterjet propulsor, which vary in technique and scope. In addition to the criterion of study type mentioned above, choice of methods depends on the answers to such questions as what performance criteria are desired, how large the hull is, what power range the pump operates in, and, as in most endeavors, time and economics available to a particular propulsion system development. Perhaps the first choice to be made is that of deciding to test a model rather than the prototype hull installation. In general, model testing allows closer control of test conditions but requires that proper scaling procedures be implemented. Modelling is often undesirable if the prototype system is itself small in size and power, and involved in low budget development programs. But considerable model testing should be performed in cases where the propulsion system is relatively large and must meet stringent requirements of performance as in important military craft applications.

For really definitive propulsion performance determination, resistance and propulsion tests must be run separately. In general, this requires some type of towing tank facility.[3] A normal resistance test should be conducted without appendages called for by the propulsion system at various trim angles, corresponding to the anticipated propelled trim. A second resistance test aimed at establishing the static effects of the waterjet hull openings on drag could be run with all propulsion system appendages in place, but with the propeller or impeller not rotating, repeating the trim angles of the first test. Finally, a propulsion test should be run to ascertain the overall effective trim and resistance which the craft experiences under the action of all drag and lift forces produced by the hull, the propulsion system, and the interaction of these forces. Testing should include effects of turning and sideslip on waterjet performance. In the case of small planing boats, it is possible to test the prototype craft in a towing basin over the actual range of design speeds. From the standpoint of achieving an ideal propulsion analysis,

this type of testing involving the prototype craft is ideal if all pertinent parameters are measured. However, the self-propulsion testing of a waterjet prototype craft in open-sea conditions (which is the case for a great percentage of actual installed waterjet performance determination)[3,14,16,17] usually does not furnish sufficient information, mainly because it is difficult to separate resistance and propulsion forces. It should be realized that it is much more difficult to obtain detailed performance data on waterjet systems than on propeller systems since the required appendages can be removed easily in the latter case. Further, the conducting of bare hull resistance tests and the determination of the propulsor thrust add to these difficulties. As stated earlier in the section on efficiency, if the goal is to compare propulsion efficiencies of two different propulsors, a comparison of shp's should suffice.

Some difficulty exists when attempts are made to separate dynamic testing of the propulsor and hull. Testing complexities will vary depending on whether a test is being conducted to predict the overall performance of a waterjet-propelled model which is free to pitch and heave or to characterize the propulsor performance, in which case the hull (or portion of the hull) is restrained in trim and heave. From the section on efficiency, it was concluded that a definitive performance criterion, $\eta_{D_{waterjet}}$, is:

$$\eta_{D_{waterjet}} = \eta_{pump} \times \eta_{jet} \times \eta_{system} \times (1-t) \qquad [10]$$

$$= \eta_T \,(1-t)$$

Any good prediction of the performance must include a reasonable estimate of (1-t). References 3, 4, 14, 19, and 21 through 26, which contain performance data, include calculations of η_T but not η_D.

The experimental work which has been done, as listed in Table 2, includes the hull-inlet subsystem which has been investigated by the authors of References 3, 19, and 22. Actual prototype craft installations have been tested and the results reported in References 3, 14, 16, and 17, all

of which contain static and dynamic test results, except Reference 3 which contains only dynamic results. Reference 18 presents an example of testing a unit in a stationary condition in a flow channel. The boat tests reported in References 14, 16, and 17 are relatively complete in the measurement of dynamic waterjet performance.

Experimental Procedures

The following are examples of methods of determining hydrodynamic propulsion performance characteristics of installed waterjet systems, listed along with the type of study for which the procedure is applicable.

1. Design. Test a waterjet-propelled hull model having both hull and internal pumping system scaled to the same linear ratio. This procedure is often impractical because of the expense in complete modelling of pumps. In addition, although scaling hull speed by Froude number and machinery speed by specific speed are compatible as far as producing the proper scaled internal-flow velocity, the range of model ducting Reynolds number will be lower than full scale and must be maintained above 1×10^5 (based on pipe diameter) in order to keep the model internal-flow pressure drop reasonable.

2. Design. Test a hull model having the proper external propulsion system characteristics of the inlet. This procedure is recommended for propulsion tests of the hull inlet/diffuser component. It requires the use of a "sucker" pump which establishes the correct scaled flow velocity at the waterjet inlet and means to maintain the full-scale cavitation number as well as to simulate the full-scale boundary layer. LITTLE SQUIRT[19] tests and tests of the hydrofoil craft-type inlets in the LUMF facility utilized this technique.

3. Design. Test a prototype craft at full-scale speeds in a towing tank and measure towed and propelled performance separately. This method has the advantage of alleviating scaling problems. However, for most testing tanks, it is limited to boat hulls no greater than about 20 feet in length and 8- to 9-foot beam, and to waterjet-system horsepowers of about 200 to 300.

4. Design or Research. Test a prototype waterjet propulsion system mounted on a "mockup" of a portion of the prototype hull which is fixed in trim and heave. Such a test could be run in a towing basin or a circulating free-surface channel. An example of the latter is reported in Reference 18. This procedure requires that the hull-inlet flow conditions be known and simulated on the "mockup."*

5. Performance. Test a prototype installation in open sea and measure P_S and P_T (by jet flow). Most of the published data available in this study pertaining to installed propulsion performance were acquired by this method. It is the cheapest and easiest test procedure. Advantages include the fact that there are no scaling problems; disadvantages are that there is less control of weather and test conditions, and it is not possible to separate resistance and propulsion forces from these measurements. Hence it is more difficult to improve performance.

6. Performance or Design. Test a prototype craft in open-sea conditions and measure thrust reaction and inlet drag, in addition to the other usual pertinent quantities. This approach would provide significantly more data for determining η_D than would Method 5. (See References 16 and 17.)

7. Performance. Test a prototype system or component on a hull on which auxiliary propulsors such as engine/propellers or aircraft deck-mounted jet engines can very effectively be used to help propel the hull so that the water pump can be tested at various combinations of thrust and ship speed. This provides performance data on the pump or inlet of a general nature with less dependence on the hull than for a fixed thrust/speed characteristic test setup.

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*A very important consideration is involved in testing waterjet ingestion systems in hull models or mockups mounted stationary in flow channels. Unless the transverse hull dimension is small compared to channel width, it is doubtful that meaningful magnitudes of the added hull drag from interaction of the induced flow by the waterjet system will be obtained.

In summary, the significant points of this section are:

1. Model testing or testing of waterjet propulsion system components in cavitation or other specialized facilities becomes feasible during preliminary design of systems requiring high efficiency.

2. Modelling of entire installed waterjet propulsion systems is made difficult, or impossible, if requirements include scaling of Froude, cavitation, and Reynolds numbers simultaneously.

3. The inlet and critical hull section can be model tested independent of the rest of the waterjet propulsion system if an auxiliary "sucker" pump is used.

4. If Froude and cavitation numbers are maintained, proper C_p distribution of the model inlet and diffuser will result.

5. Internal flow scaling should entail holding C_p and Reynolds numbers simultaneously for scaling pressure and viscous forces.

6. Shear stress scaling depends on the Reynolds number and relative roughness (e/d) effects on the dynamic pressure ($\frac{1}{2}\rho V^2$).

7. For installed waterjet propulsion systems, a definitive test of performance requires separation of resistance and propulsion forces.

8. A waterjet propulsion system may create a more significant overall effect on hull performance than does a more conventional propulsor. Thus resistance measured in nonpropelled drag tests is less indicative of the actual dynamic resistance which the hull experiences in the self-propelled mode for a waterjet propulsor.

9. Experimenters might be encouraged to attempt full-scale testing in order to alleviate the problems of modelling. However, full-scale testing provides significant measurement difficulties such as separating resistance and propulsion factors.

10. A type of "open-water" propulsion test for a waterjet propulsor could be run with a suitable hull simulation inlet. It requires testing a prototype waterjet over a range of trims, boat speeds, inlet velocity ratios, and yaw conditions in order to provide adequate performance data

from which extrapolation can be made when actual hull dynamic characteristics become known.

11. Several waterjet test stands have been specifically built for testing a complete propulsor under simulated inflow conditions, prior to dynamic testing.

GENERAL AND FEASIBILITY LITERATURE SURVEY

A large portion of the existing waterjet propulsion literature deals with general considerations of and feasibility studies for the application of waterjet systems to various types of marine craft. At the same time, considerable emphasis in the area of military ship and boat designs has recently been placed on feasibility studies which attempt to consider all significant engineering aspects of a design, integrally with the intended mission of the craft. As in many associated areas of technology, it is obvious that the availability of high-speed computers has encouraged designers and planners to conduct more studies of this type. Certainly, feasibility studies which consider mission, structures, propulsion, etc. are necessary at some point in the technological development process. Consequently, without well thought-out sound scientific-type feasibility considerations for specific applications, the full effectiveness of the waterjet propulsor cannot be realized.

The waterjet propulsion system is a special-purpose propulsor which is probably superior to other types for some specific applications, but, with the passing of time, "tradeoff" analyses become more critical to good system application. Thus the reports and papers on waterjet propulsion dealing with application feasibility studies are worthwhile, but:

1. Systematic theoretical and experimental work now needs to be done on system design and performance evaluation.

2. Feasibility and general studies need factual, verified scientific evidence for performance factors such as loss coefficients, efficiencies of systems, etc.

Indeed, in a final analysis, a system may or may not be "feasible" for a

particular application depending on the actual system efficiency, and it is unlikely that this can be determined by "guess work." Some of the papers are inherently limited in value since they contain unproven overly optimistic or overly pessimistic performance coefficients; however, practically every reference makes some contribution to the technology. References 22, 23, 24, and 61 relate to studies of feasibility of applying waterjet propulsion to certain mission craft. A much larger number of the references were found to contain information on general considerations for application of waterjet propulsion to various types of craft. These reports include References 1, 3, 4, 7, 8, 9, 19, 21, 22, 23, 24, 25, 50, 58, and 60 through 67. A brief summary of each of these reports is contained in the annotated bibliography list at the end of the paper.

CONCLUSIONS

In the Introduction, a statement of the scope of this report included:

1. A critical survey of the pertinent technical literature with emphasis on the significant problems known to exist.

2. A discussion of theoretical and experimental techniques required for the determination of performance of components and complete waterjet systems.

3. A review of the state of the art regarding the knowns and unknowns of waterjet performance. Recommendations for the use of performance parameters and techniques for evaluating performance.

4. An annotated bibliography of the reference material pertinent to the technology of waterjet propulsion.

Certain conclusions drawn from the survey, which pertain directly to the above goals, are set forth below:

1. Waterjet propulsors are a special type of marine propulsive device. They possess certain advantages over conventional propellers, including the elimination of underwater appendages, the elimination of complex

right-angle transmission systems in certain craft, and, in general, a freer choice of propulsor location.

2. The disadvantages of waterjets as compared to conventional propellers include generally higher weight, more horsepower to perform a particular powering function, and, by nature of the hull inlet, they provide an additional area of potential cavitation problems.

3. Hydrodynamic performance of waterjet-propelled craft should be based on determination of propulsive efficiency η_D, which is defined as

$$\frac{P_E}{P_D} = \frac{RV}{P_D} = \eta_{pump} \times \eta_{jet} \times \eta_{system} \times \eta_{hull/inlet}$$

where

$$\eta_{hull/inlet} = (1-t) = \frac{R}{T}$$

4. Precise determination of η_D is difficult and is not necessary for comparing hydrodynamic performance of two or more competitive propulsors on the same hull, in which case shaft horsepowers P_S should be compared. However, high η_D becomes critical in designs wherein the ratio of fuel weight to gross weight is high, as in long-range ocean vehicles.

5. Momentum theory has been used to show that high ideal jet efficiency requires a low ratio of jet velocity to craft velocity as well as low system (inlet and ducting) losses. The calculation of real jet system efficiency by simple momentum theory is not an accurate approach to the determination of system performance.

6. Certain misconceptions pertaining to various efficiencies have been noted in the literature which tend to confuse proper performance comparisons. These include the misuse of propulsive efficiency ($\eta_D = \frac{RV}{P_D}$) with thrust efficiency ($\eta_T = \frac{TV}{P_S}$) as well as of pump efficiency (η_{pump}) with propeller efficiency (η_P). Actually, $\eta_P = \eta_{pump} \times \eta_{jet}$.

7. As in the field of propeller technology, the choice of performance measurements and parameters tends to depend greatly on the relative ease with which these terms can be obtained. It is recommended that good waterjet parameters include dimensionless: flow coefficient Φ, head coefficient K_H, torque coefficient K_q, specific speed or shape number $N_{S_{dimensionless}}$, suction specific speed $S_{S_{dimensionless}}$, and for the pumps, Thoma cavitation number σ_t.

8. The design of specialized waterjet propulsion pumps is needed to provide pumps which convert the mechanical energy of the prime mover directly to kinetic energy with little increase of potential energy, as is found in conventional civil engineering pumps. Considerable efforts are being made to develop waterjet pumps with rocket-inducer impellers due to the comparable range of cavitation numbers required of pumps for these two applications.

9. Considerable research is urgently needed in the area of waterjet inlet technology. This need focuses on the requirement for hard (experimental) data for flush inlets of the planing boat type and semi-flush/ram inlets designed for high-speed CAB ships, such data to include effects of yaw and sideslip on inlet performance.

10. Good inlet design encompasses: providing an adequate flow, having low internal loss coupled with low hull drag, and having high resistance to cavitation. Inlets for craft which plane from an initial displacement condition must perform satisfactorily at takeoff during which internal lip cavitation is likely and at high-speed cruise at which external lip cavitation can cause high drag. The use of variable geometry inlets may alleviate the design problem.

11. Although certain craft application designs necessitate extensive water ducting for systems requiring high overall efficiency, careful consideration must be given to minimization of ducting. Considerable published empirical data will aid in this respect in preliminary design.

12. The determination of waterjet performance of a jet-propelled hull requires special consideration. A waterjet may create a more significant effect on hull performance than does a propeller. As in the case of

conventional propulsion, a definitive performance evaluation (breaking down losses, etc.) necessitates the separation of resistance and propulsion forces. Depending on the size and power range of a particular craft, definitive evaluation may be accomplished by model-scale or full-scale testing.

13. It is felt that satisfactory modelling of the hull inlet-diffuser subsystem can be achieved if a suitable auxiliary suction pump is used to provide internal inlet suction. This pump should be operated to provide a flow rate $Q = A_j V_j$ where $A_{j_{model}}/A_{j_{prototype}} = 1/\lambda$ and $V_{j_m}/V_{j_p} = \sqrt{1/\lambda}$.

14. A type of "open-water" propulsion test of a waterjet propulsion system could be run with a suitable hull simulation inlet. It requires running over a range of trims, boat speeds, inlet velocity ratios, and yaw conditions in order to provide adequate performance data from which extrapolations can be made when hull dynamic characteristics become known.

15. Several commercial waterjet propulsion test stands have been specifically built for testing a complete propulsor under variable simulated inflow conditions, prior to dynamic testing.

Two basic shortcomings were found to prevail within the existing waterjet literature. First, a lack of experimental data and synthesized design methods was noted and, second, a number of design parameters were found to be loosely defined. Suitable progress in the improvement of waterjet propulsion performance will require extensive research and development work in the areas of propulsion system and hull design. This work should be built upon the proper use of performance parameters and evaluation techniques. It is hoped that the attempt made here to survey the state of the art will provide some guidance to workers in the field of technology of waterjet propulsion.

ACKNOWLEDGMENT

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LIST OF REFERENCES AND ANNOTATED BIBLIOGRAPHY

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2. Papir, A.N., "Axial Pumps of Waterjet Propulsion Systems," Shipbuilding Publishing Hotse (translation), Leningrad (1965).

(Russian) - An extensive coverage of axial pumps of waterjet propulsion system. Paper outlines the problem of waterjet propulsion and then treats pump to comply. Considers momentum theory, blade design, cavitation, modelling and pump testing, pump parameters, proper drive system, rotor forces, and lattice.

3. Schuster, S., et al. "On Certain Problems of Waterjet Propulsion," DTMB Translation 306 (Aug 1962).

Lecture. History of and design principles of waterjet propulsion. Survey of intermittent water propulsion systems. Considerations of model testing discussed and a curve of results for a model test presented. Graphs of several European waterjet installations with sparse static and dynamic performance results.

4. Engel, Cochran, and Delao, M. (Buehler Corporation), "Use of Axial Flow Pumps for Marine Propulsion," SAE, Detroit Meeting (1962), Paper No. 4420 (Jan 1962).

Contains statements of the relative merits of waterjet propulsion when compared with propellers. General performance curves are presented and conclusions (not substantiated by experimental tests) are given. Good discussions of waterjet history and boat testing procedures are included. Some of the problems still facing waterjet propulsion development are listed.

5. Cobb, B., Jr., "River Patrol Boat for Vietnam," Yachting (Dec 1966).

Historical note on the development of this important craft.

6. Smith, M.S., "Tomorrow's Water Craft Will Use Water Jets — How and Why," Great Lakes Section of Society of Small Craft Designers (Apr 1965).

A short, interesting discussion of waterjet propulsion of small craft. The paper makes reasonable statements on the advantages and disadvantages of waterjets.

7. Wechsler, L., "Where Are Marine Power Plants Headed?" SNAME Paper No. 20, Spring Meeting (May 1966).

Paper discusses extent to which power plants, transmission systems, and propulsors limit speed of: 100-ton GEMS, 100-ton hydrofoils, 5000-ton CAB, 5000- and 10,000-ton displacement ships; claims state of the art can provide machinery needed in next 10 years if developmental work is done on turbines, reduction gear, propellers, and pumps.

8. Sheets, H. and Mantle, P., "Air Cushion Craft Propulsion," AIAA Paper No. 66-731, Los Angeles, California (Aug 1966).

Electric Boat Company engineers discuss advantages of various propulsion devices for air-cushion craft.

9. Gabrielli, G. and von Karman, T., "What Price Speed?" Mechanical Engineering (Oct 1950), p. 775.

This interesting paper presents a graphical representation (Karman-Gabrielli line) of minimum power requirements for given maximum speeds of a wide range of vehicles.

10. Rossell, H.E. and Chapman, L.B., "Principles of Naval Architecture," SNAME Publications, Vol. II (1955).

Authoritative textbook on naval architecture. A useful reference containing standard definitions of performance parameters.

11. Saunders, H.E., "Hydrodynamics in Ship Design," SNAME Publications, Vols. I and II (1957).

Authoritative textbook on ship hydrodynamics; valuable reference book.

12. Kuchmann and Weber, "Aerodynamics of Propulsion," McGraw-Hill Book Co., Inc., New York (1953).

A textbook containing a complete treatment of propulsion analysis momentum methods.

13. Vennard, J.K., "Fluid Mechanics," Fourth Edition, John Wiley and Sons, Inc., New York (1963).

Textbook containing empirical hydraulic loss data and procedures for the treatment of duct losses. Classical pump theory.

14. Gasiunas and Lewis, "Waterjet Propulsion: A Theoretical and Experimental Investigation into Propulsion of Seacraft by Waterjets," British Institute of Mechanical Engineers, Vol. 178, Part I (1963-64).

Runs two prototypes in open water and measures gross performance and comparison between test results. P.C. is looked at. A stimulating discussion by several noted British engineers is included.

15. Delao, M.M., "Experimental Results of Low Speed Waterjet Propulsion Systems," (Buehler Corporation), AIAA Paper No. 66-718, Los Angeles, California (Aug 1966).

A Buehler pump built for hullborne propulsion of a Navy hydrofoil craft is described. Static and dynamic experimental performance tests on the 16½-inch diameter pump designed for the 9-knot craft were conducted. Specifications included a direct 2500-rpm drive, 175-horsepower, specific speed above 26,000, suction above 21,000. Problems of flow choking and head reduction by cavitation were experienced. The design approach is given with test results for 5- and 7-bladed rotors that were tested. The experience in high-speed impeller design appears limited.

16. Price, H., "Development Testing of M-185 Aquajet in the Penn-Yan Boat," Curtiss-Wright Corporation (WAD) Report No. 2 of Project XE-726 (17 Jan 1963).

The report describes Curtiss-Wright Penn-Yan boat waterjet tests. It appears to be a good experimental analysis of the performance of a 25-ft boat at speeds in excess of 34 mph. Several inlet designs

were tested (single and dual). Static and underway tests were conducted, including a powering comparison with a propeller. Engine ratings ranged from 188-238 horsepower for these tests. A discussion of the practical problems encountered, including: hydraulics, hull/pump interaction, weeds, and instrumentation. The measured horsepower data are poor, as stated by the authors.

17. Aschauer, G. (Twin Disc Clutch Company), "Waterjet Propulsion Tests," (Three reports: Oct 1962 - Apr 1963).

Cooperative testing was conducted by the Twin Disc Clutch Company and Sewart Seacraft Inc. Experimental tests were run on a commercial waterjet propulsion system (conventional and much-modified). A three-volume report covering tests of September 1962, November 1962, and April 1963 was written. These appear to be the same type of tests as reported in Reference 16. The present setup included thrust-load cells mounted under the pump mounts.

18. Contractor, D.N., "Experimental Investigation of a Waterjet for Shallow Draft Boats," Hydronautics Report TR 516-2 (May 1966).

Appears to be a good treatment of a small boat WJP installation in a "mock" test of a U. S. Army 1-ton payload, 20-knot boat. Dimensional and nondimensional performance curves are presented covering inlet conditions, drag, thrust, trim, effect of inlet vanes, and reverser, shp, and rpm. Recommended boat installations and design. Tests of a waterjet propulsion system with simulated hull in Hydronautics high-V channel.

19. Hatte, R. and Davis, H., "Selection of Hydrofoil Waterjet Propulsion Systems," AIAA Paper No. 66-732, Los Angeles, California (8-10 Aug 1966).

Hydrofoil boats – selection method for a waterjet propulsion system – recommendations for waterjet propulsion system selection criteria. Discussion of tradeoffs and system considerations. Considerable experimental ½-scale model hydrofoil inlet data, acquired on Boeing's LITTLE SQUIRT, are known to exist. Discusses ducting loss. Boeing has recently acquired data on strut ducting performance. Discusses problems facing waterjet propulsion inlets

and describes LITTLE SQUIRT.

20. Dumov, A., "Calculation of Pressure Head Characteristics of Axial Helical Impellers," Foreign Tech WPAFB, FTD-TT 63-497 (Jun 1963).

Russian method for calculation for design of axial-helical impeller, pressure head characteristics and rate of flow from impeller configuration, lifting-line theory internal hydraulic calculations, short experimental correlation test.

21. Levy, J. (Aerojet-General), "The Design of Waterjet Propulsion Systems for Hydrofoil Craft," SNAME presentation, Southern California Section (May 1964).

Discusses the duct losses. Optimization process for general waterjet propulsion installation; paper considers in general: struts, ducts, scoops, velocity ratio, nozzle depression, angle, possible pump configurations, and makes one significant statement: "Propulsion pumps, unlike C.E. pumps, require output as K.E." Performance discusses thrust versus speed and cavitation.

22. Brown, J. and Traksel, J. (Lockheed), "Waterjet Propulsion Study," Report LR-17885 (Parts 1 through 5)(1963).

Analytic study (internal flow) for pump selection. Experimental design study (Byron Jackson) in a loop facility. Extensive design procedure; feasibility studies and system layouts for hydrofoils and large displacement ships. Empirical duct data presented. Model and prototype testing. Model inlet LUMF and pump look (component) testing. Analytic computer pressure distribution study. Inlet flow tests, analytic and experimental. Considered lip design. Enclosed cavitation facility ram inlet tests (LUMF).

23. Kim, H.C., "Hydrodynamic Aspects of Internal Waterjet Propulsion," Marine Technology (Jan 1966).

Gives condenser scoop data and intelligently discusses inlet parameters and wake intake. Empirical curves presented and recommendations for applying the data to examples of waterjet ducting systems discussed. Looking at application to large ocean displacement

vessels (shown to be less efficient than propeller), author gives a practical design procedure.

24. Johnson, V., Jr., "Waterjet Propulsion for High-Speed Hydrofoil," AIAA Paper No. 64-306, Washington, D.C. (Jun-Jul 1964).

Good discussion of duct losses and other system losses. Design procedure for waterjet propulsion to hydrofoil craft. Interesting but source unknown for performance values given. An 80-knot, 500-ton craft example. Interesting pump discussion, practical considerations of size, speed, cavitation, single and double suction, discusses off-shelf state-of-art pumps and future pump layout of hydrofoil waterjet propulsion configurations.

25. Traksel, J. and Beck, W., "Waterjet Propulsion Marine Vehicles," AIAA Paper No. 62-245, San Diego, California (Mar 1965).

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General considerations and momentum theory.

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Theoretical parametric pump study, internal pump geometry and blading, generates curves of pump flow head performance with cavitation effects.

31. Aerojet-General Corporation, "Experimental Tests on Waterjet Propulsion Pumps," von Karman Center Report UW-65403 (Jan 1965).

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Textbook. Refers to existing pump theory. Classical pump theory.

33. Addison, H., "Centrifugal Pumps and Other Rotodynamic Machines," Third Edition, Chapman-Hall Ltd., London (1965).

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34. Hunsaker and Rightmyer, "Engineering Applications – Fluid Mechanics," McGraw Hill Book Co., New York (1947).

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35. Stepanoff, A.J., "Centrifugal and Axial Flow Pumps," John Wiley and Sons, Inc., New York (1948).

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37. Stripling, L. and Acosta, A.J., "Cavitation in Turbo Pumps," Transactions ASME (Sep 1962).

Authors are authorities in high-speed pump hydrodynamics. Good experimental study along with an analysis of cascade flow representing a simple cavitation model estimate of cavitation loss made and cavity shapes made, model tests done at Rocketdyne. Conclusions give points on blade profiles and suggestions for better performance.

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This report presents ram recovery and mass flow ratios for NACA submerged inlets for aircraft air ingestion. Plots of pressure distribution over the ramp and the inlet extreme given. Angle of attack was 0.2 to 1.2 deg, $M = 0.3$ to 0.875. Maximum ram recovery ratios were at $m = 0.6$ to 0.8.

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57. Hirsh and McJones (Hughes Tool Company), "Hydrostreak Water Scoop Study," Hughes Tool Report HTC 62-42 (Jul 1962).

Static experimental study in which ram inlets are subjected to free-stream jet. Data include drag, pressure coefficient, and inlet velocity ratio.

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General layout studies for hydrofoils, CABS, destroyers, and planing boats. Analytical curves of gas-turbine water-pump installation presented.

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Comparison study of the feasibility of hydrofoil propulsion (500-ton, 80-knot) by: waterjets, 90-deg drives, MARJET, air props, gas turbines, electric motors, chain drives, tape drives, inclined shafts.

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Study of waterjet propulsion application to small planing boats up to 50 feet and 40 knots, gives design procedure for power requirements and calculates efficiency.

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Hydrofoil propulsion systems, machinery propulsion plant, general discussions on various forms it can take. Paper states that "pump model testing may be very costly."

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65. Thurston, S. and Amsler, R., "A Review of Marine Propulsion Devices," AIAA Paper 65-482, San Francisco, California Meeting (Jul 1965).

A good review of major marine propulsors, including waterjet. Very general treatment.

66. Hale, M. and Norrie, D.H., "Hydrojet Propulsion Reduces Vibration," Engineering (Jul 1964).

Adelaide University, Australia, Mechanical Engineering Department. This study considers the vibration advantages of waterjet propulsion. Claims lower thrust reduction for waterjet propulsion and discusses system loss and efficiency. Relates vibration with hull forms.

67. Taggart, R., "A Development Program for an Improved Hydraulic-Jet Propulsion Device," Trelor Contract, ASNE Journal, Vol. 71 (Aug 1959).

U. S. Army Transportation Corps contract prompted the author to do a development program study for waterjet propulsion. Paper lists practical problems including hull design. Includes considerations for design of hull duct, impeller machinery, and control systems, and recommends brief experimental program for tests of hull model, duct model, and impeller.

68. "Hydrojets Are Here to Stay," Rivers and Harbors (Feb 1961).

A spirited, but naive, presentation of purported success of a device called "hydrojet." It does not appear to be very factual.

69. Lorenz, E., "Comparison between Two Methods of Marine Propulsion," Great Lakes Chapter, Society of Small Craft Designers (Jun 1963).

This short paper by a Michigan Wheel Company representative compares a waterjet installation with a conventional propeller installation and presents very limited data indicating superior efficiency of the propeller system.

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TABLE 2

Summary of Experimental Waterjet Propulsion Work

	Characteristics / Reference No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
	Pump Impeller		X								*	*	*	*	X	X					X		X							X		X	*	*	*	*
	Pump Cavitation		X												X	X							X							X		X				
	Static Inlet																						X													
	Dynamic Inlet														X								X													
Model Boat	Propulsive Efficiency, η_D																																			
	Thrust Efficiency, η_T																																			
	Pump Characteristics																																			
	Inlet Flow			X																																
	Nozzle Flow			X																																
	Thrust & Drag			X																																
	Lift																																			
	RPM																																			
	SHP																																			
	Trim & Heave			X																																
Prototype Boat	Static Inlet			X											X	X	X	X	X																	
	Dynamic Inlet			X											X	X	X	X	X																	
	Propulsive Efficiency, η_D																X																			
	Thrust Efficiency, η_T			X											X		X	X	X																	
	Pump Characteristics			X											X	X	X	X	X																	
	Inlet Flow			X											X	X	X		X																	
	Nozzle Flow			X											X	X	X	X	X																	
	RPM			X											X	X	X	X	X																	
	SHP			X											X	X	X	X	X																	
	Trim & Heave			X											X		X	X	X																	
	Boat Velocity			X											X	X	X	X	X																	

	Characteristics / Reference No.	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
	Pump Impeller	X	X	X		X	X	X	X	*														X												
	Pump Cavitation	X	X	X		X	X	X	X																											
	Static Inlet																X°	X°	X°	X°	X†	X†	X													
	Dynamic Inlet																																			
Model Boat	Propulsive Efficiency, η_D																																			
	Thrust Efficiency, η_T																																			
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*Textbook, °Marine Condenser Scoops, †Aircraft-type Inlets.

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13. ABSTRACT

Characteristics peculiar to waterjets may make this type propulsion capable of overcoming some of the problems facing high-speed marine propulsion. As a basis for judging the potential of waterjets in relation to other propulsion methods, a study was conducted to determine the state-of-the-art of waterjet technology. Available literature was surveyed with particular emphasis on: (1) performance criteria and performance data, and (2) performance evaluation and experimental techniques. A review of the existing work indicates a general lack of definitive experimental data. Although the greatest apparent need is for experimental information on the design of efficient and cavitation-free high-speed inlets, work is also needed on light-weight pumps which are capable of sustained high performance under relatively severe cavitation conditions. It was found in the literature that thrust efficiency was usually confused with propulsive efficiency. Propulsion efficiency is equivalent to the product of thrust efficiency and the hull/waterjet interaction efficiency. Therefore, propulsive efficiency is a more definitive performance parameter but is inherently more difficult to obtain. The requirement of separating resistance and propulsive forces in determining this efficiency leads to model experiments. A review of model experimental techniques and facilities shows the capability for carrying out the necessary experiments.

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